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EVAPORITIC DEPOSITS OF WESTERN CANADA

N.C. MEIJER DREES

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EVAPORITIC DEPOSITS OF WESTERN CANADA

Abstract

This compilation gives a general description from published and unpublished sources of the many Paleozoic and Mesozoic evaporitic deposits present in the Interior Plains and eastern Cordillera of Western Canada. The description of each deposit includes a discussion of the general geology, stratigraphy, paleogeography, structural geology and environment of deposition.

Some evaporitic deposits dissolve in circulating groundwater and are not exposed at the surface in their original form. The lithologic descriptions of the evaporitic deposits and the maps showing their distribution and thicknesses are thus based largely on subsurface information.

The evaporitic deposits are subdivided into minor and major deposits. The minor deposits are of Ordovician, Silurian, Mississippian, Triassic and Jurassic age. They do not contain salt and are interbedded with redbeds and/or carbonates. The major evaporitic deposits are of Cambrian and Devonian age and include thick and economically important salt beds. These deposits were studied in detail and their description includes new information.

The evaporites include many lithologies such as redbeds, anhydrite, gypsum, rock salt and potash salt. Typical lithologies of the major evaporitic deposits are described with the aid of photographs. The interpretation of the environment of deposition of the various facies in the two major evaporitic deposits is based largely on the study of cores and it is shown that the deposits include fabrics of primary and secondary origin. A substantial amount of the Devonian anhydrite and potash salt is of secondary or replacement origin.

Résumé

Sur la base de documents publiés et inédits, on donne une description des nombreux dépôts évaporitiques du Mésozoïque et du Paléozoïque, que l'on rencontre dans la plaine Intérieure et l'est de la Cordillère de l'Ouest canadien. La description de chaque dépôt inclut une étude sur la géologie générale, la stratigraphie, la paléogéographie, la géologie structurale et le milieu de sédimentation.

Certains dépôts évaporitiques se dissolvent dans les eaux souterraines en mouvement et n'apparaissent pas en surface sous leur forme originale. Les descriptions lithologiques des dépôts évaporitiques et les cartes indiquant leur épaisseur sont largement basées sur la connaissance de la géologie de subsurface.

Les dépôts évaporitiques se subdivisent en dépôts principaux et mineurs. Les seconds datent de l'Ordovicien, du Silurien, du Mississippien, du Trias et du Jurassique. Ils ne contiennent pas de sel et sont interstratifiés avec des red beds ou des carbonates, ou avec ces deux types de roches. Les dépôts évaporitiques majeurs sont du Cambrien et du Dévonien, ils se présentent en bancs épais et revêtent une importance économique, l'étude détaillée de ceux-ci a apporté dans ce domaine de nouvelles connaissances.

Les évaporites contiennent un grand nombre de faciès distincts tels que red beds, anhydrite, gypse, sel gemme et potasse; le rapport comprend des photographies de carottes de forage prélevées dans les deux principaux dépôts évaporitiques. L'interprétation du milieu de sédimentation des divers faciès identifiés dans les deux principaux dépôts évaporitiques est largement basée sur l'étude des carottes de forage, et il est démontré que ces dépôts contiennent des textures d'origine primaire et d'origine secondaire. Une proportion substantielle de l'anhydrite et de la potasse d'âge dévonien ont une origine secondaire ou sont des produits de remplacement.

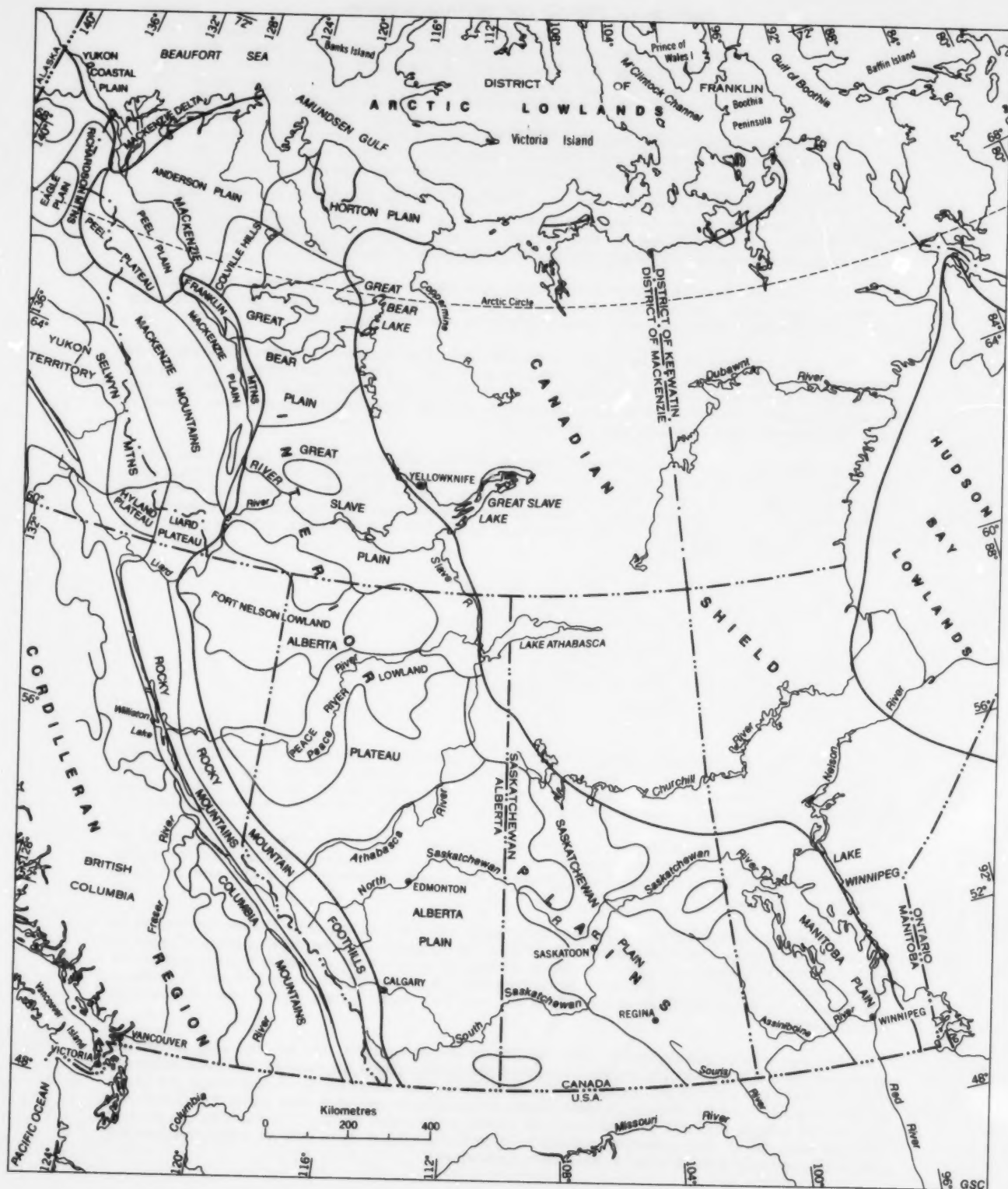


Figure 1. Physiographic regions, western Interior Plains.

EVAPORITIC DEPOSITS OF WESTERN CANADA

CHAPTER I

INTRODUCTION

The purpose of this report is to bring together useful information about the principal evaporitic deposits in Western Canada and to describe their associated salt beds in detail.

The evaporitic deposits of Western Canada contain important minerals such as sodium chloride, potash salts, and gypsum. Such minerals are used as feedstock or as additives in a number of industries. Gypsum is widely used in the manufacture of cement and plasterboard. Chlorine and caustic soda producers use salt; the rapidly expanding fertilizer industry of Saskatchewan is based on potash salt. Salt is also marketed for human consumption. Commercial use of salt in the production of de-icing chemicals is also significant.

In some parts of Western Canada, caverns were formed in the subsurface by dissolving salt. These caverns are used for the storage of oil and natural gas and it is anticipated that similar caverns may be used in the future for the disposal of suitable industrial waste materials.

In 1975, the Geological Survey of Canada, at the request of Atomic Energy of Canada Limited, initiated a project to evaluate the salt beds of Canada as potential host rocks for a nuclear waste disposal mine. During the first phase of the project the objective was to compile data and maps on all salt beds and to select for detailed study an area or a salt bed with a potential for such use. The results of the first phase of the study were compiled in a confidential, internal Geological Survey report entitled, "Evaporite deposits of Canada, Phase I - an overview". This report contains regional maps showing the distribution and thickness of the important salt beds in the subsurface of the Interior Plains of Western Canada. During the second phase of the project, the writer studied in some detail the salt beds of the Prairie Evaporite Formation in Alberta and Saskatchewan and selected four potential underground disposal sites in that formation.

Because the salt beds are significant from an economic viewpoint, the Geological Survey extended the first phase of the project to include a study of the geological setting and environment of deposition of the salt beds, so that their areal extent, stability and economic significance could be properly evaluated in the light of Canada's future needs. Because salt beds are associated with redbeds and commonly include anhydrite, gypsum and potash deposits, these evaporites were also studied.

Redbeds, bedded gypsum, anhydrite and halite are widely distributed in the subsurface of the Interior Plains of Western Canada. They are less widespread in the Rocky Mountains and Mackenzie Mountains. There is only one report of an evaporitic deposit west of the Rocky Mountains and Mackenzie Mountains and no reports have been written to describe Canadian Shield evaporites. Thus, the present report deals mainly with that part of Western Canada which lies east of the Cordilleran region and southwest or west of the Canadian Shield, an area commonly referred to in

geographical terms as the western Interior Plains. It includes the southwestern part of Manitoba, southern Saskatchewan, eastern and central Alberta, northeastern British Columbia, and the District of Mackenzie in the Northwest Territories (see Fig. 1).

Most of the evaporitic deposits, such as anhydrite, gypsum and halite are generally not exposed at the surface in their original form. Much of the knowledge of the evaporites in Western Canada is thus based on information gathered from the subsurface in the Interior Plains. A cursory survey indicates that major evaporitic deposits occur only in sedimentary rocks of Paleozoic and Mesozoic age and are absent from Proterozoic and Cenozoic strata. The depth of burial, thickness and age of the evaporites vary from place to place, and within each evaporitic succession lateral facies changes occur from redbeds to bedded anhydrite to halite, or from dolostone to anhydrite to halite. Some areas in the Interior Plains are underlain by two or three different evaporitic units.

In order to facilitate the description of the evaporitic deposits, they are subdivided into two groups. Major evaporitic deposits are thick, extensive and include interbeds of halite. Minor evaporitic deposits are relatively thin, have a local distribution, and do not include salt beds.

The major evaporitic deposits of Western Canada accumulated in sedimentary basins separated from the sea by one or several barriers. The oldest deposit is the Saline River Formation, comprising redbeds and halite. It occurs in the middle part of the Cambrian to Ordovician succession in the District of Mackenzie, Northwest Territories. Other major deposits that include salt beds are of Devonian age. They occur in the subsurface of Manitoba, Saskatchewan, Alberta, and in the southern part of the District of Mackenzie. These salt beds are interbedded with redbeds, anhydrite and carbonate.

Most minor evaporitic deposits in Western Canada are interbedded with ancient shelf deposits. They consist of interbedded anhydrite and carbonate. The oldest minor deposit is of Proterozoic age and occurs in an unnamed map unit exposed in the Mackenzie Mountains. Others are present in the Ordovician Bighorn Group and the Mississippian Charles and Mission Canyon formations of southern Saskatchewan, in the Mississippian Shunda and Debolt formations of western Alberta, and in the Triassic Charlie Lake Formation of northeastern British Columbia. The Jurassic Amaranth and Watrous formations of southern Saskatchewan and Manitoba include redbeds, gypsum and anhydrite.

Acknowledgments

This report is a compilation of information derived from different sources, all mentioned in the text. The summary discussions of the minor evaporitic deposits are wholly based on published work by other geologists. The chapter on the geology of the major evaporitic deposits is

based partly on work by others but also includes new information. Original work was done on the salt beds of the Cambrian Saline River Formation, the Devonian salt beds in the southern part of the District of Mackenzie, and the Prairie Evaporite Formation in northeastern Alberta and southwestern Saskatchewan. Subsurface information on the Devonian Elk Point Group in Alberta was purchased from Canadian Stratigraphic Services Ltd. and Digitech Systems Co., in the form of data printouts and computer plotted maps. These data and the published maps of Hamilton (1971) were used to construct the maps of the Devonian salt beds in northeastern Alberta.

An unpublished report from the Manitoba Mines Branch, written by Bannatyne and McCabe, and the maps published by

the Saskatchewan Department of Mineral Resources by Holter (1969), Lane (1959, 1964), Dunn (1975) and Kendall (1976b), were used to determine the distribution of the salt beds in Manitoba and Saskatchewan.

The writer acknowledges the help of G.R. Davies who supervised and critically read the first phase of the report. The maps, cross-sections and the text of this report were critically reviewed by D.G. Cook, B.V. Sanford, A.W. Norris and D.W. Morrow. Preliminary structural cross-sections were drafted on contract by S. Siewert. Core photographs were taken by B.C. Rutley. The photographs of the Cominco potash mine near Vanscoy have been provided as a courtesy by A.D. Mackintosh and the Potash Division of Cominco Ltd.

CHAPTER II

REGIONAL PHYSIOGRAPHY

Physiographic units

The evaporitic deposits described in this report underlie the Interior Plains of Western Canada. This region is situated between the Canadian Shield to the northeast and east and the Cordillera to the west. It is an ancient plateau with low to moderate topographic relief dissected by rivers.

The highest part of the Interior Plains is situated in western Alberta and in northeastern British Columbia. This area grades westward into the Rocky Mountain Foothills region which ranges in altitude between 915 and 1220 m (3000 and 4000 ft) above sea level. The Alberta Plain (see Fig. 1) occupies the southwestern part. It is a plateau cut by deep river valleys, which ranges in altitude between 1220 m (4000 ft) in the west to 610 m (2000 ft) in the east. The Cypress Hills in the south reach heights of over 1830 m (6000 ft).

The Alberta Plain is bordered on the east by the Saskatchewan Plain, which varies in elevation between 240 and 550 m (800 and 1800 ft). East of the Saskatchewan Plain is the Manitoba Plain, the elevations of which vary between 180 and 270 m (600 and 900 ft).

The Alberta Plain is bordered on the north by lowlands and hills. The southern part of this area was named the Alberta Plateau by Bostock (1970) and may be regarded as the northward extension of the Alberta Plain. The elevation of the hills ranges between 610 and 1220 m (2000 and 4000 ft) and for the lowlands it varies from 180 to 610 m (600 and 2000 ft).

The Alberta Plateau grades northward into an area dominated by lowlands. It includes the Great Slave, Great Bear, Horton, Anderson and Peel plains and the Colville Hills (see Fig. 1). Elevations in the lowlands range from 90 to 305 m (300 to 1000 ft). Those in the Hills and in the Peel Plateau range from 305 to 760 m (1000 to 2500 ft).

Drainage

The Interior Plains of Western Canada are dissected by a number of rivers that flow from west to east or from south to north. The Alberta, Saskatchewan and Manitoba plains are drained by the Assiniboine and the North and South

Saskatchewan rivers, which flow eastward into Lake Winnipegosis. Lake Winnipegosis is connected to Hudson Bay by the Nelson River. The Alberta Plateau and the southern part of the District of Mackenzie are drained by a system of rivers that includes the Athabasca, Peace, Slave, Hay, Liard, Great Bear, and Mackenzie. In this system, the water flows in a general northward direction toward the Beaufort Sea. The Anderson and Horton plains are drained by smaller rivers such as the Anderson, Horton and Hornaday, which flow northward into the Beaufort Sea.

Surficial deposits

The Interior Plains are almost entirely covered by a thick mantle of glacial and postglacial deposits of Pleistocene age. Some of the present-day landforms were sculptured by glacial action or were produced by a combination of glacial and fluvial action. Other landforms, including river valleys, lakes, river terraces, beach ridges and sand dunes, were formed after the glacial period. Much of the area lying above the level of the former glacial lakes has the typical undulating topography of ground moraine.

Bedrock

Exposures of bedrock in the Interior Plains are rare and limited in size because of the thick cover of glacial deposits. Only in the larger river valleys and in hillside scarps can bedrock be seen at the surface.

Two types of bedrock are present. The most widespread consists of poorly consolidated, Paleocene or Cretaceous shale and sandstone (see Fig. 2). The interbedded shale and sandstone succession is gently dipping or flat-lying. It unconformably overlies well indurated carbonate, evaporitic or clastic rocks of Cambrian to Jurassic age.

The Southern Plains are underlain by Paleocene or Cretaceous strata. Along the southeastern margin of the Canadian Shield these flat-lying beds have been removed by erosion and carbonate rocks of Devonian, Silurian and Ordovician age form the bedrock.

In the Northern Plains, the Cretaceous cover is largely removed by erosion. The underlying strata of Cambrian, Ordovician, Silurian and Devonian age form the bedrock in the low-lying areas whereas the Cretaceous beds cap the more elevated parts (see Fig. 2).

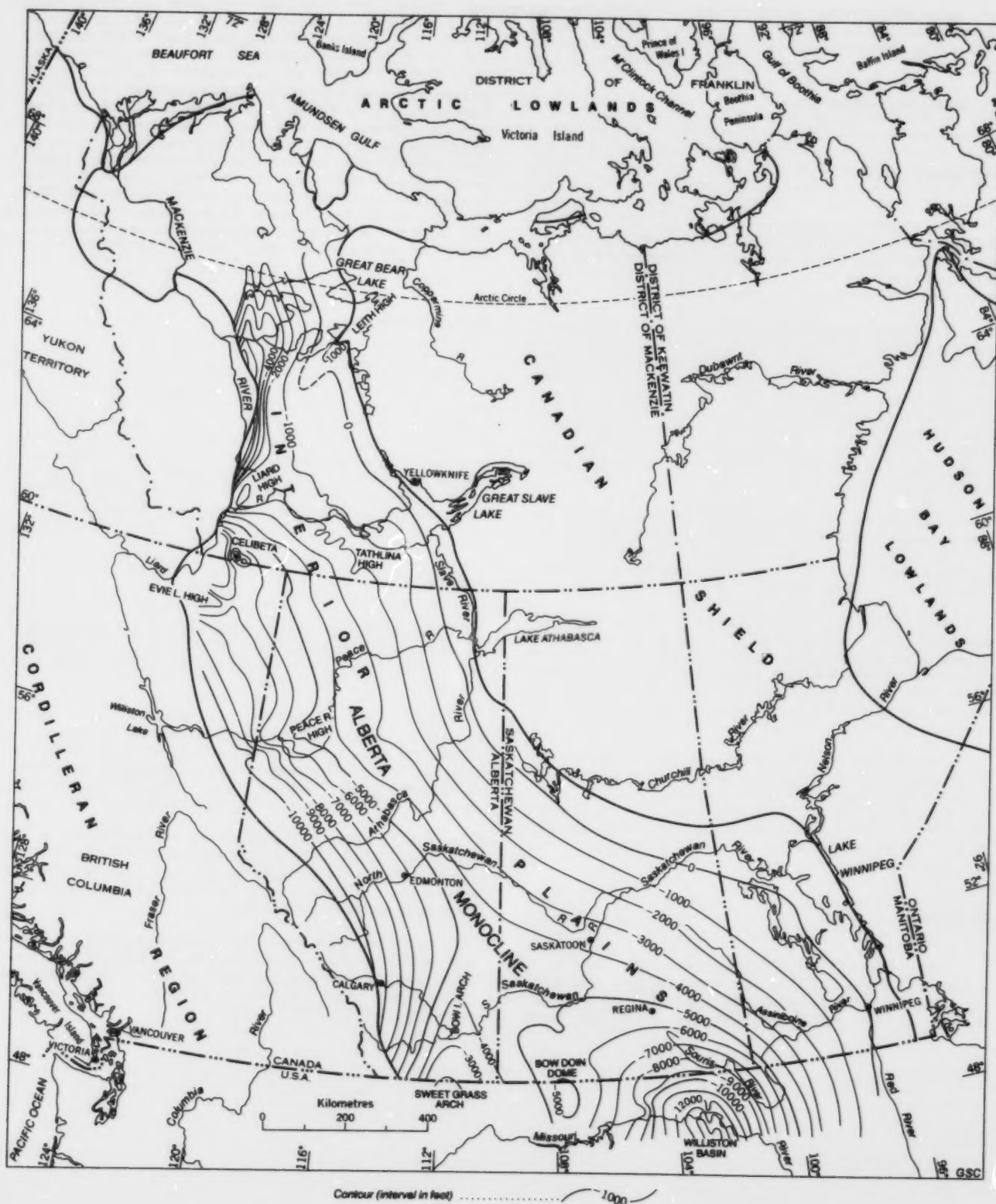


Figure 3. Structural contour map of Precambrian surface, western Interior Plains.

CHAPTER III

REGIONAL GEOLOGICAL SETTING

The Interior Plains of Western Canada are underlain by the westward extension of the Canadian Shield. The extension of this Precambrian terrane is sometimes referred to as "basement". It dips gently to the southwest or west and is mappable in the subsurface as a relatively flat surface (see Fig. 3). This surface is overlain by a largely undisturbed wedge of sedimentary rocks, which attains a thickness of over 6000 m (20 000 ft) in the west and gradually thins to zero in a northeasterly direction. This wedge of sedimentary rocks is named the Interior Platform (Douglas et al., 1970).

In the Foothills region and in the western part of the Cordillera, the wedge of sedimentary rocks is folded and thrust-faulted over the granitic basement. In the central and western part of the Cordillera, the structure of the sediments is further complicated by the presence of large, granitic intrusions. The mountainous area in which the sedimentary rocks are disturbed and uplifted was named the Cordilleran Orogen (Douglas et al., 1970).

The three principal geological provinces are outlined in Figure 2. They include the Canadian Shield in the east, the Interior Platform in the centre, and the Cordilleran Orogen in the west.

A. Interior Platform

An outline of the internal structure and the geological history of the Interior Platform was given by Douglas, Gabrielse, Wheeler, Stott and Belyea (in Douglas et al., 1970). The stratigraphy and facies relationships of the rock succession in the subsurface of the southern part of the Interior Platform were discussed in more detail by several contributors to the "Geological History of Western Canada", edited by McCrossan and Glaister (1964). The subsurface geology of the northern part of the platform was described by other workers in "The Future Petroleum Provinces of Canada", edited by McCrossan (1973). These geologists have recognized eight major sedimentary successions in the Interior Platform, separated by periods of uplift and erosion. These successions can be separated from each other by differences in lithology, stratigraphic position, fossil content, and areal distribution.

Depositional successions

The oldest succession is of Late Proterozoic or Helikian age and is widely distributed in the subsurface of the District of Mackenzie, Northwest Territories, and in northeastern British Columbia. It is unconformably overlain by the Cambrian to Lower Ordovician rock succession, which has a wide distribution in the subsurface, but is absent in northern Alberta and the southern part of the District of Mackenzie. The Middle Ordovician to Silurian rocks have a more restricted distribution in the subsurface and occur only in the

northern part of the District of Mackenzie and in southeastern Alberta, southern Saskatchewan and southwestern Manitoba. The Devonian to Mississippian succession is again widely distributed and includes most of the evaporites discussed in this report. The Permian and Triassic successions have a limited distribution in the subsurface; they are confined to west-central Alberta and northeastern British Columbia and also occur in the Mackenzie Delta area of the Northwest Territories. The Jurassic succession occurs in southern Saskatchewan, western Alberta, northeastern British Columbia, and in the northwestern part of the District of Mackenzie. The Cretaceous to Early Tertiary succession lies at or near the surface over extensive areas of the Interior Platform (see Fig. 2).

The Paleozoic sedimentary successions fringe the western margin of the Canadian Shield. There is evidence, in the form of facies changes and variations in thickness, that these successions are erosional remnants of ancient shelf deposits, which accumulated west of a landmass composed of Precambrian granitic and metamorphic rocks. The Cambrian to Lower Ordovician and the Upper Ordovician to Silurian successions in the southern part of the Interior Platform have been preserved in a circular, structural depression known as the Williston Basin (Porter and Fuller, 1959). These successions attained their greatest thickness on the Interior Platform in southeastern Saskatchewan and North Dakota. The lower part of the Devonian to Mississippian succession accumulated in a paleotopographic depression known as the Elk Point depositional basin, which is centred in northeastern Alberta.

The Permian, Triassic and Jurassic successions are relatively thin and poorly represented in the Interior Platform. The Permian, Triassic and Jurassic beds are mainly distributed along the western edge of the Interior Platform and reach their maximum thicknesses in the Cordilleran Orogen. The Jurassic succession is also present in southern Saskatchewan and southwestern Manitoba.

During Cretaceous and early Tertiary time, the region west of the Interior Platform was uplifted and acted as a source for sediments, while the emergent region in the east diminished in size. During this time, the Interior Platform region was part of a north-south trending, elongate basin, which could be traced from the Arctic Ocean to the Gulf of Mexico.

Epitrogenic events

The sedimentary successions accumulated during periods in which sea level rose and large areas of the Interior Platform were below or at sea level. Rock successions which accumulated because of local subsidence of the earth's crust are also apparent. Geological evidence indicates that most of the area now occupied by the Cordilleran Orogen was subsiding during Paleozoic and early Mesozoic time while the Interior Platform was relatively stable. However, there is evidence, in the form of widely distributed unconformities below and above the sedimentary successions of the Interior Platform, that sea level rose during some periods and fell during others. Alternatively, there were periods of subsidence and periods of uplift and erosion. It is impossible

to ascertain whether an unconformity is due to a regional uplift of the Earth's crust or to a fall in sea level and, in this report, the term epeirogenesis is used for any such event that caused widespread erosion. However, there is no doubt that the "First and second-order global cycles of relative change of sea level during Phanerozoic time" of Vail et al. (1977, Fig. 1) had an effect on the sedimentary history of the Interior Platform.

Some of the epeirogenic events lasted as long or longer than the periods during which deposition took place. In the eastern part of the Interior Platform, for example, the Devonian to Mississippian and Ordovician to Silurian rock successions are directly overlain by Lower Cretaceous rocks. Pennsylvanian, Permian and Triassic strata are absent.

Each epeirogenic event is mappable as an erosional unconformity and some unconformities may be regarded as buried paleotopographic surfaces. The paleotopographic surfaces are irregular and include areas of high and low elevation. Paleotopographic high areas can be outlined in the subsurface on isopachous and structural maps. The larger ones have been previously mapped on paleotopographic reconstructions as "arches", "highs" or "uplifts". The larger paleotopographic low areas have been referred to as "basins" or "subbasins", and there are examples of paleotopographic "escarpments".

There are several paleotopographic high areas that were uplifted during a period of general subsidence. These tectonically positive features are delineated by steeply dipping faults which also affect the granitic basement. Examples of such local tectonic uplifts are the Campbell Uplift, Keele Arch, Aklavik Arch, Tathlina Uplift, certain areas on Peace River Arch, and the Sweetgrass Arch (see Fig. 3 in part). Some of these uplifts had a great influence on the surrounding depositional environment. They restricted the inflow of seawater and acted as local sources of detrital sediment.

Orogenic events

In contrast to epeirogenic events, which are associated with vertical movements of the Earth's crust, orogenic events are associated with lateral movements of the crust. These lateral movements are responsible for the formation of folded and thrust-faulted orogens. Because the Interior Platform includes only the undisturbed region east of the Cordillera, the effects of the Laramide Orogeny were relatively minor and are classified as epeirogenic. The earliest record of events associated with the Laramide Orogeny is the erosional unconformity that separates Upper Jurassic from Lower Cretaceous beds in the southern Interior Platform. Elsewhere on the Platform, this unconformity separates Lower Cretaceous beds from beds ranging in age from Precambrian to Mississippian.

In the western part of the Interior Platform, the Cretaceous beds include conglomerates with chert pebbles derived from eroded Paleozoic strata. The source area of the pebbles and the source area of several widespread, eastward thinning, sandstone units in the overlying Cretaceous and Paleocene rocks lie to the west of the Interior Platform. This requires that, during the Cretaceous and Paleocene periods, parts of the Cordillera were emergent and subjected to erosion.

Present-day geologic and physiographic configurations of the Interior Platform suggest that the region was uplifted

after the formation of the Cordilleran Orogen during the Laramide Orogeny.

B. Cordilleran Orogen

The geology of the Cordilleran Orogen has been described by Douglas et al. (1970). Because only the eastern part of this region locally contains evaporitic deposits, the following discussion is restricted to this part.

The eastern Cordillera is, in many respects, transitional to the Interior Platform and includes the Rocky Mountains in the south and the Mackenzie Mountains in the north. In general, these two elements include the same rock successions as the adjacent parts of the Interior Platform. The Paleozoic and Early Mesozoic successions are more complete in the eastern Cordilleran region, because they have been less affected by the erosional events that accompanied the epeirogenic uplifts in the Interior Platform.

Southern Rocky Mountains

In the southern Rocky Mountains, the sedimentary rocks were pushed eastward over a relatively passive, granitic basement during the Laramide Orogeny. Compression resulted in the formation of north-south trending folds and gently westward dipping thrust faults (see Bally et al., 1966). In general, the structural deformation increases in intensity from east to west. The higher and more westerly thrust sheets were formed prior to the lower and more easterly thrust sheets. The folding and thrusting itself may not have produced the high mountains (Cook, 1960): they originated during the last stage of the Laramide Orogeny, and are the result of uplift and erosion.

Northern Rocky Mountains and Mackenzie Mountains

The northern Rocky Mountains and the Mackenzie Foldbelt are known only from surface geology, and it has not been demonstrated by seismic data that the granitic basement is involved in thrust faulting. In the Mackenzie Foldbelt, the granitic basement is overlain by a thick succession of Late Proterozoic rocks. Evidence from seismic data in the Colville Hills indicates that these rocks and the overlying Paleozoic strata are cut by steeply dipping normal faults (Davis and Willott, 1978), but it is not known if the same situation occurs below the Mackenzie Mountains.

The Mackenzie Foldbelt was described by Norris (1972). It includes the Franklin Mountains, the Mackenzie Plain and the Mackenzie Mountains. This foldbelt forms a great arc which extends northeastward toward the continental interior (see Fig. 1). It includes a southern flank made up of right-hand *en echelon* folds, in which the individual folds trend northward; and a northern flank consisting of left-hand *en echelon* folds, in which the individual folds trend northwestward. The eastern ranges of the Mackenzie Mountains consist of west-dipping homoclinal structures in Paleozoic carbonates and evaporites, underlain by thrust faults. There is evidence in cores from several wells

that the Cambrian and Devonian evaporitic rocks were, at least locally, deformed more intensively than the overlying and intervening carbonates.

Norris (1972) concluded that the Late Proterozoic and Phanerozoic rocks in the Mackenzie Foldbelt were transported differentially to the northeast over a relatively

passive basement, during the Laramide Orogeny. Although thrust faults are present in the eastern parts of the Mackenzie Foldbelt (Cook and Aitken, 1976), Davis and Willott (1978) maintained that most of the deformation in the Franklin Mountains and Colville Hills was controlled by a regional system of basement faults.

GEOLOGY OF EVAPORITIC DEPOSITS

A. Nature and distribution

In the following discussions, the term "evaporitic deposit" is used in a broad sense and includes the minerals that accumulated by evaporation of a body of water, together with interbedded or associated sedimentary rocks. Some sedimentary rocks included with the evaporites contain anhydrite or salt, in the form of cement, void fillers or nodules. They comprise redbeds, all deposits of anhydrite, gypsum and salt, and some types of dolomite.

Lithological varieties

The term redbeds is used for successions of red and green mottled shale, sandy shale or dolomitic shale, interbedded with reddish brown sandstone, dolomitic sandstone or siltstone, and are known to include gypsum, anhydrite or halite in the form of beds, nodules, crystals or veins.

Different types of anhydrite deposits were subdivided and named by Maiklem et al. (1969). In Figure 4, this subdivision is simplified and includes crystallotopic, nodular, and bedded anhydrite deposits. Crystallotopic and nodular anhydrites are secondary deposits occurring in a matrix of sedimentary rock. Bedded anhydrite includes relatively pure deposits with very little or no matrix. Subfelled anhydrite includes dolomitic or argillaceous anhydrite with recognizable sedimentary structures. These rocks are named according to the classification proposed in Figure 5. The felled and aligned-felled anhydrites are finely to coarsely recrystallized. They may show relict structures of replacement or sedimentary origin.

Deposits of gypsum do not occur in the deep subsurface of Western Canada. They are present at the surface or in the shallow subsurface in close association with anhydrite. Gypsum formed in the shallow subsurface by the hydration of anhydrite under the influence of groundwater. Because the transformation from anhydrite to gypsum is associated with an increase in volume and gypsum is soluble in water, the original anhydrite deposit disintegrated into a "solution breccia". The gypsum found in the shallow subsurface occurs in veins or as inclusions in the anhydrite or interbedded carbonate. At the surface, gypsum forms massive beds or occurs as a matrix in massive carbonate breccia.

Salt deposits have been leached from the surface and shallow subsurface by circulating groundwater and are only present in the deep subsurface. They include three facies: light grey halite, reddish brown halite, and sylvite. The light grey halite facies consists of relatively pure, semi-translucent halite with inclusions of light grey anhydrite. It includes thin interbeds of light grey, sedimentary anhydrite or siliceous shale. The reddish brown halite includes yellowish brown, greyish brown or reddish brown, semi-translucent halite, with varying amounts of reddish brown or grey shale between the crystals, and also

includes interbeds of reddish brown and grey shale. This facies commonly contains less than 5 per cent sylvite and grades into the sylvite facies. The sylvite facies is reddish brown or red and is a coarse crystalline mixture of sylvite, halite and clay. It locally includes carnallite.

Dolomitic beds occur commonly in association with halite and anhydrite. The light brown, aphanitic or micro-crystalline dolostones commonly contain nodular replacement anhydrite, anhydrite cement or scattered crystals of anhydrite and halite. The dolomitic beds also contain sedimentary structures or fossils.

Depositional features

The evaporitic deposits of Western Canada have certain depositional features in common that warrant discussion. The most striking feature is uniformity of the lithologic succession in a particular evaporitic deposit over great distances, and the presence of many, widespread, stratigraphic markers which were deposited as nearly horizontal beds. Other features are the absence of interbedded medium- or coarse-grained clastic rocks near the edges of evaporitic basins, and the predominance of the more soluble minerals in the central parts of the basins.

It is, therefore, important to analyse the depositional pattern of each evaporitic deposit within a sedimentary basin. Such an analysis may suggest that deposition was either largely controlled by local subsidence or by eustatic changes in sea level. For instance, the depositional analysis of the Triassic succession in Western Canada by Barss et al. suggests that, during the Triassic, the area presently occupied by part of the Cordilleran Orogen was subsiding and formed a geosynclinal trough. The Triassic evaporites are part of the miogeosynclinal deposits that accumulated along the eastern edge of this trough. These deposits thicken westward and unconformably overlie Paleozoic rocks. They accumulated as a result of a relative rise in sea level during early Triassic time. The analysis of the Devonian Elk Point Group in Western Canada by Grayston et al. (1964) indicates that the evaporitic deposits in the southern part of the Interior Platform did not accumulate in a geosynclinal trough. The geographical migration, throughout Devonian time, of the boundaries between the various facies in the Elk Point basin; the widespread occurrence within the succession of thin, regressive and transgressive units; and the general absence of features of synsedimentary, tectonic origin, strongly suggest that the Elk Point evaporites were deposited as a result of a gradual, relative rise in sea level.

The evaporitic deposits and their facies equivalents are commonly composed of repetitive sequences of a small number of lithologies. Individual rock units in such depositional sequences or "cycles" (see Duff et al., 1967) can be mapped over large areas and remain remarkably constant in thickness and lithology. The evaporitic sequences are commonly separated from each other by sharp contacts, which mark periods of nondeposition, subaerial exposure, or erosion. The lower unit of such a sequence, in many places, is fossiliferous and may include mud pebbles at the base. The upper part contains the evaporitic deposits, commonly in the form of sedimentary or replacement anhydrite. If the upper part of such a sedimentary sequence includes structures

Deposit consists of macroscopic anhydrite crystals or crystal aggregates in a non-anhydritic matrix	Deposit consists of distinct nodules or nodular beds in a non-anhydritic matrix			Deposit is a relatively pure, laminated or bedded anhydrite without nodular or mosaic structures		
CRYSTALLOTOPIC	NODULAR			BEDDED		
	Nodules or beds are separated	Nodules or beds are partly separated	Matrix is almost absent	Micro to fine blocky crystals	Fine to coarse, elongate crystals are not aligned	Fine to coarse, elongate crystals are aligned
	Nodular or bedded nodular anhydrite	Nodular mosaic or bedded nodular-mosaic anhydrite	Massive mosaic or massive nodular-mosaic anhydrite	Subfelted anhydrite	Felted anhydrite	Aligned-felted anhydrite

GSC

Figure 4. Classification of anhydritic deposits.

related to subaerial exposure, or is cut off at the top by a surface representing a period of emergence, the complete succession can be either interpreted as a regressive, progradational tidal flat sequence (Wilson, 1975; p. 33-55) or as a desiccated, lagoonal deposit (Kendall, 1976a, p. 53-57). If the first interpretation is correct, the lateral equivalents of the sequence situated in the central part of the depositional basin are dominated by fossiliferous beds of marine origin. If the second interpretation applies, the central part of the depositional basin is occupied by anhydrite and halite.

When seawater evaporates, the concentration of the carbonates, sulphates and chlorides increases to the point where one or more salts will precipitate. The sequence in which these salts precipitate has been studied during the evaporation of seawater in solar ponds. Calcite (CaCO_3) and gypsum ($\text{CaSO}_4 \cdot 2\text{H}_2\text{O}$) are the first salts to precipitate, followed by halite (NaCl). Halite precipitates only after the original volume of the seawater is reduced by 91.7 per cent. Magnesium and potash salts in the form of Epsomite ($\text{MgSO}_4 \cdot 7\text{H}_2\text{O}$), Mirabilite ($\text{Na}_2\text{SO}_4 \cdot 10\text{H}_2\text{O}$), Kainite ($\text{MgSO}_4 \cdot \text{KCl} \cdot 3\text{H}_2\text{O}$) and finally Carnallite ($\text{KCl} \cdot \text{MgCl}_2 \cdot 6\text{H}_2\text{O}$) and Bischoffite ($\text{MgCl}_2 \cdot 6\text{H}_2\text{O}$) follow in a predictable succession, as evaporation continues, and are temperature dependent. One would thus expect to find a similar sequence of salts in the evaporitic deposits of Western Canada. This is not the case.

Most salt deposits in Western Canada contain only anhydrite or halite mixed with anhydrite or clay. Some of these salt deposits are more than 60 m (200 ft) thick and contain only traces of potash salt. The brines from which they precipitated may thus never have reached the extreme concentrations necessary to produce potash salts. Only the Devonian Prairie Evaporite Formation is known to contain potash salts. These occur at three levels in the central part of the evaporitic deposit (Holter, 1969). The potash is present as Sylvite (KCl) and Carnallite ($\text{KCl} \cdot \text{MgCl}_2 \cdot 6\text{H}_2\text{O}$). Magnesium salts such as Epsomite and Kainite are absent. The brines from which these potash salts originated must have been devoid of sulphate cations.

The process by which the Cambrian and Devonian salt deposits were formed was apparently far more complex than that of the simple, present day precipitation process involving evaporation of seawater in solar ponds. It is probable that the Cambrian and Devonian salt beds were formed during many stages of precipitation and partial dissolution, and that the brines in most evaporitic basins were not concentrated enough to prevent dissolution of earlier precipitated potash salts. Only the brines in the Devonian Prairie Evaporite basin became concentrated enough to prevent the dissolution of potash salts. The depositional history of this basin includes long periods of complete desiccation during which the composition of the first generation of salt deposits could have been modified by the action of ground- and rain-water.

Allochthonous sediments					
Containing less than 10 percent very coarse (larger than 1 mm) particles			Containing more than 10 percent very coarse particles		
Containing mud matrix composed of particles smaller than 0.03 mm.		No mud matrix			
Coarse particles are supported by a mud matrix		The coarse particles are not supported by a mud matrix		The very coarse particles are supported by a matrix	The very coarse particles are not supported by a matrix
Less than 10 percent of particles are larger than 0.1 mm	More than 10 percent of particles are larger than 0.1 mm				
Mudstone	Wackestone	Packstone	Grainstone	Floatstone	Rudstone

GSC

Figure 5. Classification of sedimentary rocks according to depositional texture.

If the sulphates and chlorides originated from seawater, large amounts of water must have evaporated in the salt basins because seawater contains only 3.5 per cent of various salts in solution. In order to explain the great thickness of some salt deposits, one has to assume that the evaporitic basin was somehow connected with the ocean so that water loss by evaporation in the basin was offset by inflow of seawater. Restrictions in the influx of fresh seawater would eventually cause the precipitation of salt in the basin. When an equilibrium between subsidence, influx of seawater, evaporation and precipitation is achieved, thick beds of halite may accumulate. If the influx of seawater halts, then the water level in the basin drops, the wetted land surface decreases in size, and the chemistry of the brine changes during the precipitation process. Complete desiccation does not mean that the deposition of salt is halted, it only results in a redistribution of the most soluble salts in the shallow subsurface and local topographic depressions (Valyashko, 1972). Gravity and evaporation produce a gradient in the desiccated basin so that groundwater flows upward and toward the basin centre. The brine in the shallow subsurface of the basin centre eventually becomes chemically quite different; it only superficially resembles a brine derived from seawater by direct evaporation. The salt deposits which are derived from seawater contain the same ratio of Bromine to Chlorine or Rubidium to Chlorine as seawater. In many Devonian saltbeds in Western Canada, the ratios are markedly different from those of seawater (see Holter, 1969, p. 34-36).

Stratigraphy and regional distribution

The stratigraphic succession and the approximate age of the evaporitic deposits in Western Canada are shown in Figure 6. Evaporitic deposits composed of anhydrite are present in the Helikian rocks of Mackenzie Mountains in the Northwest Territories. They also occur in the Ordovician to Silurian carbonates in southwestern Manitoba and southeastern Saskatchewan. Anhydrite deposits are also present in the Upper Devonian and Mississippian carbonates of southwestern Manitoba, southern Saskatchewan, Alberta and northeastern British Columbia and in the Triassic beds of northwestern Alberta and northeastern British Columbia. Redbeds, dolomite and anhydrite of a possible Jurassic age occur in southeastern Manitoba and southern Saskatchewan. Cambrian salt occurs interbedded with redbeds and anhydrite in the northern part of the District of Mackenzie, Northwest Territories and Devonian salt deposits occur interbedded with carbonates, anhydrite and redbeds in the three prairie provinces and the southern part of the District of Mackenzie, Northwest Territories.

Very little is known about the evaporites which are associated with the Helikian carbonates, and such deposits are not described in this report. The reader is referred to the report by Aitken et al. (1973, p. 15) in which the presence of white gypsum beds in map unit H5 is mentioned. Much more is known about the Paleozoic and Mesozoic evaporites and these are described in the following chapters.

The older Paleozoic evaporites are relatively well preserved in the subsurface, and it is possible to map a large part of the original, depositional limits. The younger deposits are unconformably overlain by Cretaceous rocks and some parts were removed by pre-Cretaceous erosion. It is thus difficult to reconstruct the original configuration or discuss the paleogeographic situation of these deposits.

In the following two chapters, the evaporitic deposits are treated as two groups. The minor evaporitic deposits, which lack interbeds of salt, are discussed first and the two major evaporitic deposits, which include salt beds, are discussed later.

B. Geology of minor evaporitic deposits

Four minor evaporitic deposits are briefly described in the following discussion. They are the anhydrite deposits of the Bighorn and Interlake groups of southeastern Saskatchewan and Manitoba of Ordovician and Silurian age respectively; the anhydrite deposits of Mississippian age in the Debolt and Mount Head formations of western Alberta, and the Madison, Mission Canyon, Charles and Kibbey formations of southeastern Saskatchewan and Manitoba; the redbeds and anhydrite deposits of the Charlie Lake and Whitehorse formations of Upper Triassic age in northeastern British Columbia and west central Alberta; and the redbeds, gypsum and anhydrite beds of the Amaranth and Watrous formations of questionable Jurassic age in southern Saskatchewan and Manitoba (see Fig. 6).

The minor evaporitic deposits were not studied by the author and the following description is based entirely on work by others mentioned in the references and text.

1. Ordovician and Silurian evaporites

Introduction

The lower part of the Middle Ordovician to Silurian succession, including its evaporites, accumulated in a roughly circular paleotopographic depression or depositional basin located in northwestern North Dakota, northeastern Montana, and southern Saskatchewan (see Fig. 7). The paleotopographic depression was carved by erosion in Cambrian to Lower Ordovician sedimentary rocks. The Middle Ordovician to Silurian succession is unconformably overlain by Middle Devonian rocks and the most complete sections are found in the subsurface of North Dakota.

Middle Ordovician to Silurian carbonates are exposed along the southwestern margin of the Canadian Shield; however, the anhydrite interbeds are present only in the subsurface.

Stratigraphy

The Middle Ordovician to Silurian carbonates of the Southern Plains are subdivided into two parts. Ross (1957) introduced the term Bighorn Group for the lower part of the succession and Baillie (1951) introduced the term Interlake Group for the upper part of the succession.

The evaporites of the Bighorn Group in southern Saskatchewan were mapped and described by Kendall (1976a), who recognized a fourfold subdivision in the subsurface, and described, in ascending order, the Yeoman, Herald, Stony

Mountain and Stonewall formations. Previous workers used the term Red River Formation for the combined Yeoman and Herald formations (Porter and Fuller, 1959 and 1964; Kent, 1960; Evans, 1960). The formations comprising the Bighorn Group are mainly of Late Ordovician age, and the Stonewall Formation may include the boundary between the Ordovician and Silurian (Brindle, 1960).

The Interlake Group was defined in the outcrop area of Manitoba and originally included the Stonewall Formation (Baillie, 1957). Porter and Fuller (1959 and 1964), Kent (1960), and Kendall (1976a) mapped the Interlake Group in the subsurface, but excluded the Stonewall Formation from the original definition. The Interlake Group is sparsely fossiliferous and of Silurian age (Baillie, 1951; Stearn, 1956).

Evaporites of the Bighorn Group

Kendall (1976a) mapped the anhydrite beds in the subsurface of southeastern Saskatchewan as submembers of five evaporitic units. He named the evaporitic units, in ascending order: the Lake Alma, Coronach, Gunton, Lower Stonewall, and Upper Stonewall anhydrites.

The Lake Alma anhydrite occurs at the top of the Lake Alma Member in the Herald Formation, and corresponds to the "P and Q evaporites" of Porter and Fuller (1959), and the "A evaporite" of Kent (1960). It reaches a maximum thickness of 7.6 m (25 ft) in the central part of the Williston Basin and thins in all directions away from this depositional centre, due in part to a facies change from anhydrite to dense dolostone, and to truncation below an erosional surface (Kendall, 1976a, p. 27). In the central part of the depositional basin, the "Lake Alma anhydrite" overlies slightly argillaceous, bedded or laminated, crypto- to micro-crystalline dolostone, and it consists of two anhydrite beds separated by a dolomitic interval in the middle. Near the zero edge of the "Lake Alma anhydrite" the upper bed has changed to dolomite or is cut out. The lower anhydrite bed includes laminated anhydrite, closely interlaminated anhydrite and dolostone, and nodular to nodular-bedded anhydrite. The upper bed is composed of nodular and nodular-bedded anhydrite. Kendall (1976a, Fig. 14) has mapped the distribution of the "Lake Alma anhydrite" in southeastern Saskatchewan.

The "Coronach anhydrite" forms the upper part of the Coronach member of the Herald Formation and correlates with the "R evaporite" of Porter and Fuller (1959). It reaches a maximum thickness of 4.5 m (15 ft) in the central part of the Williston Basin and is not as widely distributed as the "Lake Alma anhydrite" (see Kendall, 1976a, Fig. 13). The thinning and disappearance of the "Coronach anhydrite" appears to be due to truncation below an erosional surface (Kendall, 1976a, p. 29). The "Coronach anhydrite" consists of thinly bedded to nodular-bedded anhydrite.

The "Gunton anhydrite" is the upper submember of the Gunton member of the Stony Mountain Formation and correlates with the "G evaporite" of Porter and Fuller (1959), and the "Gunton Evaporite" of Kent (1960). The submember is only about 1.5 m (5 ft) thick in the central part of the Williston Basin (Kent, 1960, p. 21), but has a wider distribution than the "Coronach anhydrite" (see Kendall, 1976a, Fig. 19). The "Gunton anhydrite" thins and disappears because of a lateral facies change to dolostone (Kent, 1960, p. 21). The submember consists of thinly bedded anhydrite or interlaminated dolostone and anhydrite. The interlaminated facies is distinguished by the presence of light coloured, displacive anhydrite nodules (Kendall, 1976a, p. 40).

The "Lower Stonewall anhydrite" occurs in the lower part of the Stonewall Formation and correlates with the Stonewall Evaporite of Kent (1960) and the "S" evaporite of Porter and Fuller (1959, Fig. 13). The anhydrite unit has a maximum thickness of about 3.6 m (12 ft) in the central part of the depositional basin, and it is assumed that the anhydrite changes laterally to anhydritic dolostone along the margin of the basin. This unit consists of either nodular anhydrite with thin, wavy beds and laminae of light brown and brown dolostone, or nodular mosaic-anhydrite (Kendall, 1976a).

The "Upper Stonewall anhydrite" was cored south of the international boundary in North Dakota (Porter and Fuller, 1959, p. 160). Borehole log correlations suggest that this evaporitic member may also be present in southern Saskatchewan (Kendall, 1976a, p. 44) but cores are lacking. The "Upper Stonewall anhydrite" is 1.2 m (4 ft) thick in North Dakota.

Evaporites of the Interlake Group

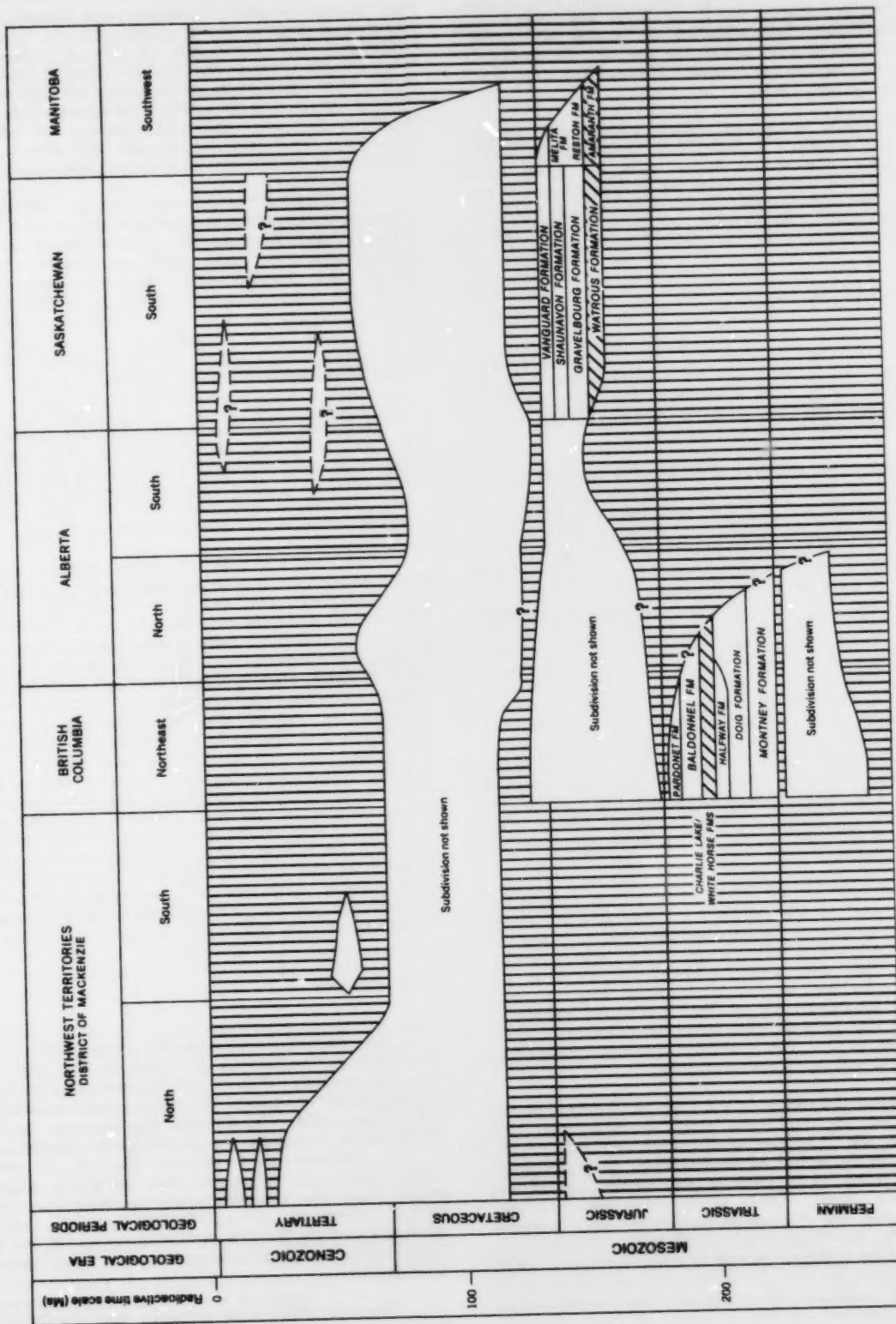
Mappable anhydrite units are not present in the Interlake Group, but Baillie (1951, p. 18) described the presence of "hopper-shaped" halite moulds and impressions of halite crystals in light coloured, silty and sandy, dense to finely crystalline dolostone from the lower part of the Interlake Group in the outcrop area of Manitoba.

Porter and Fuller (1959) subdivided the Interlake Group in the subsurface into three informal units on the basis of thin, widespread, silty and sandy marker beds. They noted the presence of highly resistant and dense interbeds of silty and sandy, anhydritic dolostone in the upper part of their "Lower Interlake Beds". Near the eastern rim of the Williston Basin, another argillaceous and sandy interval in the "Middle Interlake Beds" includes thin beds of red shale with polygonal mud cracks, and very anhydritic dolostone. The "Upper Interlake Beds" of Porter and Fuller (1959, 1964) are only present in the central part of the Williston Basin. In the subsurface of southeastern Saskatchewan they consist of "a monotonous succession of white and gray microgranular, rocks, alternating between heavily dolomitized, vuggy, fragmental limestones and dense porcellaneous, highly anhydritic dolomites". This succession reaches a maximum thickness of about 54.8 m (180 ft). The somewhat evaporitic facies passes northward into a facies characterized by "clotted dolomitic mudstone and pseudo-oolitic rocks" (Porter and Fuller, 1959, p. 165).

Paleogeography

The present limit of the Ordovician to Silurian succession in the Interior Platform is the result of pre-Devonian erosion. Facies and thickness variations of the formations in the southern part of the Interior Plains (Porter and Fuller, 1964, Fig. 4), and the presence of a basal, transgressive, sandstone facies (the Little Doctor Sandstone) in the southern part of the District of Mackenzie (Meijer Drees, 1975), suggest that there was a paleotopographic high area in northern Alberta during Late Ordovician time. However, the similarity between the Silurian carbonates in the District of Mackenzie and in the Southern Plains indicates that this barrier may not have existed during Silurian time.

There is little or no evidence that the Ordovician to Silurian succession in the Southern Plains was separated by a paleotopographic barrier from the successions in the southern



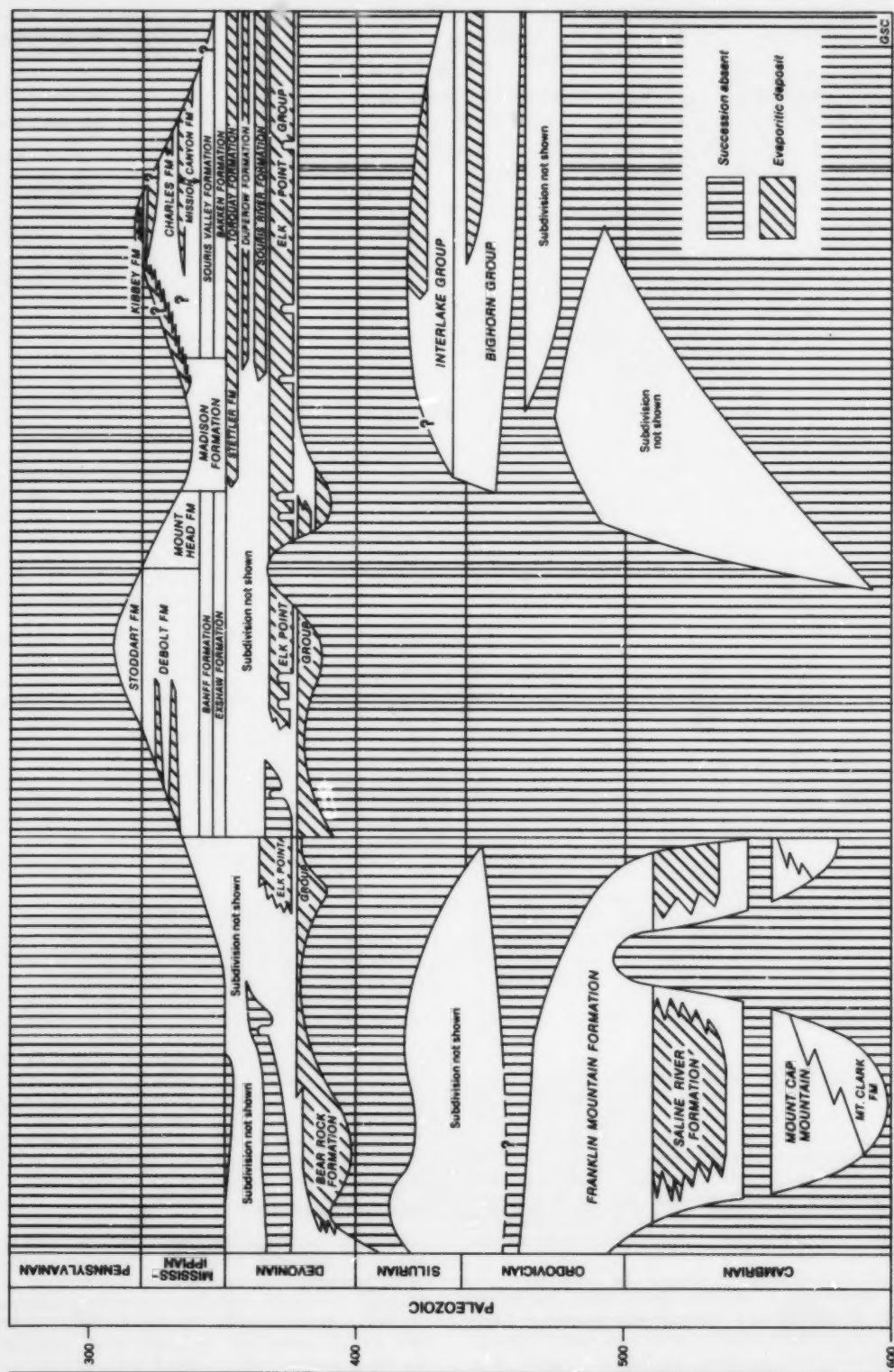


Figure 6. Phanerozoic rock successions including evaporites, western Interior Plains.

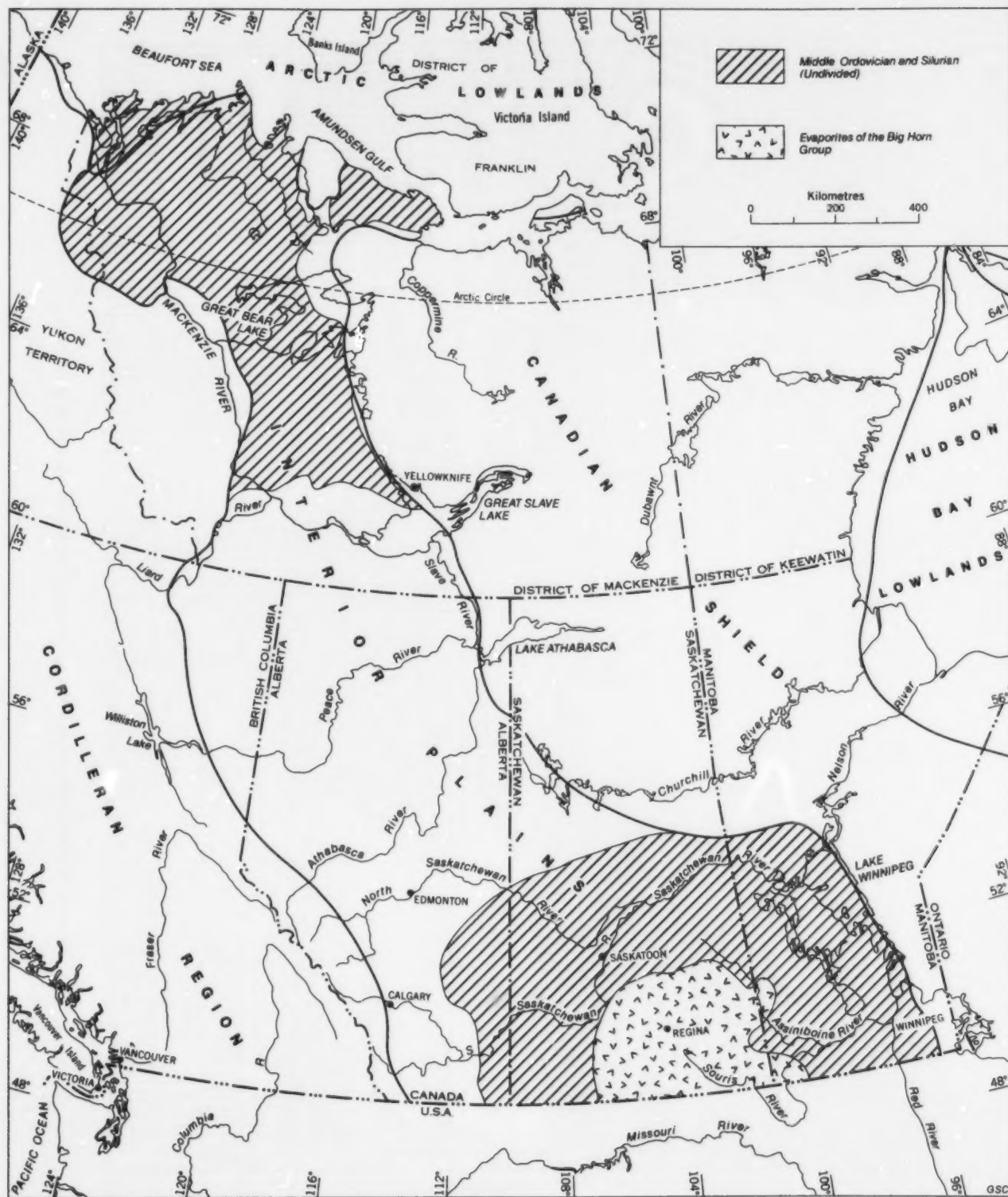


Figure 7. Distribution of Middle Ordovician to Silurian strata and evaporites.

part of the Hudson Bay region and the Great Lakes districts. It is thus possible that at one time the entire mid-continent of North America was covered by Silurian carbonates (see Douglas et al., 1970, p. 385-386).

Environment of deposition

Porter and Fuller (1959) noted the presence of a repetitive succession of rock types in the Bighorn Group. They suggested that the anhydrite beds form the middle part of a depositional "cycle", which includes fragmental limestone, argillaceous dolostone, anhydrite, argillaceous dolostone, and fragmental limestone. These "cycles" are well developed in the Stonewall and Herald formations. Kendall (1976a) studied the sedimentary structures of the carbonates and anhydrites in the Bighorn Group of southeastern Saskatchewan and their relationship with the cyclic deposits. He noted that the argillaceous marker beds, regarded as non-sequential by Porter and Fuller (1959), actually form the base of the sedimentary succession. He described incomplete and complete "cycles". The complete "cycles" grade upward into anhydrite, the incomplete "cycles" do not. Each complete "cycle" consists of four units: a basal marker bed; a fossiliferous biomicrite with or without dolomitic mottles; an unfossiliferous and commonly dolomitized, laminated carbonate; and an anhydritic dolostone or anhydrite. The base of each succession is marked by a sharp contact, which in places is overlain by a thin, argillaceous pebble-bed. Thus, in a strict sense, the succession of lithologies is not cyclic and is better described as sequential.

The anhydrite beds of the Bighorn Group are interbedded or interlaminated with crypto- or micro-crystalline dolostone, and contain sedimentary structures such as graded beds and scoured surfaces. However, the original bedding is commonly disturbed by recrystallization of the anhydrite interbeds, resulting in nodular-bedded and distorted bedding structures. Kendall (1976a) also recognized displaceable nodules of relatively pure anhydrite in the Stony Mountain and Stonewall formations. These nodules resemble those described by Shearman (1966), Kinsman (1966), and Butler (1970) from the Recent supratidal sabkha deposits along the Trucial coast in the Persian Gulf (Kendall, 1976).

According to Kendall (1976), the Herald, Stony Mountain and Stonewall formations accumulated in a semi-restricted basin. He suggested that during periods of excessive evaporation, the salinity of the water in the basin increased and the deposition of fossiliferous biomicrites was followed by unfossiliferous, laminated, carbonate mudstones. Further restriction in the influx of seawater resulted in a lowering of the water level by evaporite drawdown. During this period, the basin was greatly reduced in size. Sulphate and carbonate muds were deposited in the central part of the basin, while secondary replacement anhydrite accumulated in the shallow subsurface of the intermittently exposed marginal parts. Kendall thus explains the sequential nature of the upper part of the Bighorn Group as the result of both restriction in the influx of seawater and excessive evaporation.

Roehl (1967) studied the sedimentary structures preserved in the rocks of the Stonewall Formation and the Lower Interlake beds of eastern Montana and compared them with the sedimentary structures of Recent tidal flat deposits in the Bahamas. He recognized structures of subtidal, intertidal, supratidal and subaerial environments in the Ordovician and Silurian succession. The nodular beds of replacement anhydrite in the Lower Interlake beds were

stated to have a supratidal origin. Roehl (*ibid.*) explained the sequential nature of the beds in terms of depositional progradation in a slowly subsiding basin (see also Meissner, 1972).

Structural geology

The evaporites of Ordovician and Silurian age have been preserved in a large circular depression, the Williston Basin. The Lower Paleozoic beds and the interbedded evaporites in Manitoba and southern Saskatchewan dip toward the centre of this structural depression, which is located in western North Dakota (see Fig. 3).

Structural contour maps of the anhydrite beds of the Bighorn and Interlake groups are not available, but the configuration of these beds should closely resemble the configuration of the formations of which they are a part. The structural contour maps of the Yeoman Formation (Kent, 1960, Fig. 8), the Stonewall Formation (Kendall, 1976a, Fig. 26) and the Lower Interlake beds (Porter and Fuller, 1959, Fig. 19) are all very similar, and closely follow the configuration of the underlying Winnipeg Formation (Paterson, 1971, Fig. 5) and the Precambrian surface, as mapped by Porter and Fuller (1959) and Burwash et al. (1964). The structural contour maps on the top of the Ordovician to Silurian succession (Porter and Fuller, 1959, 1964) are less pronounced, but still show the outline of the Williston Basin and the elongate depression that connects that basin with the Alberta monocline.

2. Mississippian evaporites

Introduction

Evaporitic beds occur in the upper part of the Devonian to Mississippian succession. The upper part of this succession accumulated on a broad shelf, southwest of an ancient landmass situated somewhere in the Canadian Shield region. It is impossible to reconstruct the original position of the ancient shelf because the landward side of the Upper Devonian and Mississippian deposits is not preserved. However, the general distribution of the evaporitic and carbonate facies suggests that the shelf included an embayment in the southeastern part of the Interior Plains region. The location of this embayment more or less coincides with the location of the present Williston Basin (see Fig. 8).

The Mississippian strata conformably overlie Upper Devonian beds and the general facies distribution of both the Mississippian and the Upper Devonian successions is similar. In southern Saskatchewan, in the Rocky Mountains, and in certain areas of west-central Alberta, clastic rocks of Pennsylvanian age overlie Mississippian carbonates. Elsewhere in the Interior Plains, Mississippian beds are unconformably overlain by Permian, Triassic, Jurassic or Cretaceous rocks.

Because of erosional truncation, the Mississippian succession thins from southwest to northeast. The succession does not reach the outcrop area southwest of the Canadian Shield. However, rocks of Mississippian age are exposed in the Rocky Mountains and in the Foothills region of southwestern Alberta.

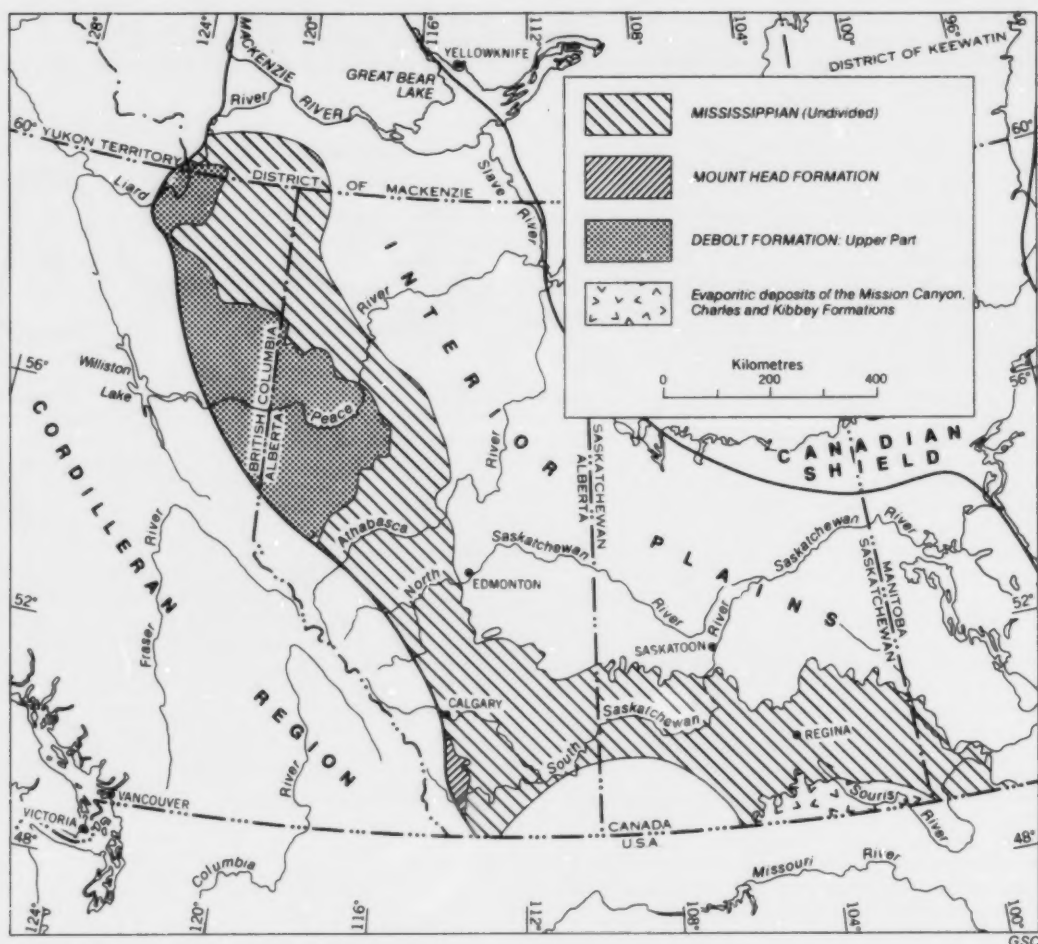


Figure 8. Distribution of Mississippian strata and evaporites, western Interior Plains.

Stratigraphy

Complete sections of the Mississippian succession are present in the subsurface of southern Saskatchewan, Montana and Wyoming, in the subsurface of west-central Alberta, and in the southern Rocky Mountains (see Macauley et al., 1964). Thus, there are three sets of formal nomenclature in Western Canada. Each subdivision includes several formations, and only the two lower formations are mappable over a large area in the Interior Plains region. These are the Exshaw and Banff formations of Alberta and their stratigraphic equivalents in Saskatchewan and Manitoba, the Bakken and Souris Valley formations.

The upper and middle parts of the Mississippian succession are only partly preserved. They consist of carbonates and locally include interbeds of anhydrite or salt. The subdivision of the middle and upper parts is based on local marker beds or lithology. In Saskatchewan, the Souris Valley Formation is overlain by the Madison Formation (Kent,

1974) or the Mission Canyon Formation (Thomas, 1954; Macauley et al., 1964). In the southern part of the Rocky Mountains and the adjacent Interior Plains, the Banff Formation is overlain, in ascending order, by the Pekisko, Shunda, Turner Valley and Mount Head formations (Macauley et al., 1964). Only the Mount Head Formation locally includes anhydrite. In the subsurface of west-central Alberta and northeastern British Columbia, the Pekisko Formation has disappeared because of a lateral facies change, and the Banff Formation is directly overlain by the Shunda Formation. The equivalent of the Turner Valley and Mount Head formations is named the Debolt Formation. Only the upper part of the Debolt Formation includes anhydrite interbeds.

The evaporitic deposits of the Mississippian succession are described in two parts: the first includes the deposits in western Alberta and northeastern British Columbia that accumulated on the ancient continental shelf east of the Cordilleran geosyncline (Douglas et al., 1970); the second includes those in the subsurface of southern Saskatchewan and Manitoba that accumulated in an embayment.

Evaporites of the Debolt and Mount Head formations

The evaporites in the upper part of the Mississippian succession of Alberta and British Columbia consist of anhydritic dolostone and anhydrite. These deposits have not yet been mapped as separate units in the subsurface, although they are easily recognizable from borehole logs.

In the subsurface of west-central Alberta and in northeastern British Columbia, the evaporitic beds of Mississippian age were placed in the upper part of the Debolt Formation (Macauley, 1958). The borehole logs of the type section of the Debolt Formation suggest that the anhydritic beds vary in thickness between 1.2 and 6 m (4 and 20 ft). The logs also suggest that the anhydritic beds grade downward into thick carbonate beds but are sharply overlain by thin, argillaceous "marker beds".

The upper part of the Debolt Formation is more or less equivalent to the Mount Head of southwestern Alberta, and both formations were mapped as a single map unit by Macauley et al. (1964). The Mount Head Formation is exposed in the Foothills region and in the Rocky Mountains (see Fig. 8). The formation in the outcrop area near Banff was described in detail by Macqueen and Bamber (1968). It is a succession of alternating recessive and resistant limestone, dolostone, calcareous and/or dolomitic shale and includes local breccia interbeds. Douglas (1953, 1958) and Macqueen and Bamber (1968) recognized eight members of which three have an evaporitic character. The three evaporitic members grade laterally northwestward into crinoidal or oolitic limestone. The evaporitic members vary in thickness between 7.6 and 67.7 m (25 and 222 ft) and consist of yellowish brown, recessive weathering, thinly bedded and laminated, silty or very fine sandy, microcrystalline dolostone with interbeds of sandstone, micritic limestone, and dolostone breccia. The dolostone breccia includes angular, pebble-sized dolostone fragments and chert fragments set in a matrix of finely crystalline dolomite or vuggy, coarsely crystalline calcite. Conglomerates composed of subrounded to well rounded, elongate dolomite pebbles are locally present in one member as lenticular interbeds.

Illing (1959, p. 51) stated that the two upper evaporitic members of Douglas (1953) correlate with two anhydrite beds in the subsurface, but did not elaborate on this. The Mount Head Formation in the subsurface is overlain by rocks of Jurassic age with an erosional contact, and the regional distribution of the Mount Head in the Foothills region is limited to the southwestern part of Alberta (see Douglas and Harker, 1958, Fig. 1; Macauley et al., 1964, figs. 7-8; and Rupp, 1969, Fig. 2). No reports are available on the evaporitic deposits of the Mount Head Formation in the subsurface.

Evaporites of the Madison, Mission Canyon, Charles and Kibbey formations

In southwestern Saskatchewan, the upper part of the Mississippian succession is represented by the Madison Formation, which includes stratigraphic equivalents of the Banff and Souris Valley formations (Kent, 1974). In the subsurface, the Madison Formation is composed of bioclastic limestone and includes dolomite and anhydrite interbeds near its eroded top. According to Kent (1974), the anhydrite is only present in the area where the Madison limestone is overlain by evaporitic deposits of Jurassic age. The anhydrite occurs as "blebs" or nodules in layers that cut either horizontally or obliquely across the bedding, or as fracture and vein fillings in carbonate beds.

In the subsurface of southeastern Saskatchewan, eastern Montana and Manitoba, the Madison limestone is overlain by evaporitic deposits of the Charles Formation. The contact between the evaporitic and carbonate facies steps down, in a stratigraphic sense, from west to east. The facies change cuts across the boundaries between units that were named "Beds" not formations (see Thomas, 1954; Fuller, 1956; Edie, 1958; Fuzesy, 1960 and McCabe, 1959; Christopher et al., 1971, Fig. 14). These "Beds" are mappable with the aid of nonsequential, argillaceous markers. However, most authors have retained the terms Mission Canyon, Charles, and Kibbey formations for the subdivision of the upper part of the Mississippian succession in the subsurface of southeastern Saskatchewan and Manitoba.

The evaporitic deposits were described by Fuller (1956) and Fuzesy (1960, 1966, 1973). They occur in two forms. The first type of evaporitic deposit is associated with the erosional unconformity at the top of the Mississippian beds, which cuts downsection, in all directions, from a centre located in central-south Saskatchewan. In those areas where the Mississippian carbonates are overlain by Jurassic evaporites, the limestone beds are partly recrystallized to dolostone or anhydrite. Anhydrite also occurs in fractures, veins and nodules (McCabe, 1963; Kendall, 1975). This replacement facies can be up to 9 m (30 ft) thick (Fuzesy, 1966).

The second type of anhydrite occurs as bedded deposits in the upper part of sedimentary "cycles" (Fuller, 1956). Fuzesy (1973) recognized two types of anhydrite: interbedded and laminated deposits of anhydritic dolostone; and dolomitic anhydrite and nodular or nodular-bedded anhydrite (sabkha anhydrite). The anhydrite beds are recognizable on borehole logs and were mapped in the subsurface by Fuzesy (1960) as subunits of log-marker defined map units or "Beds". He used the stratigraphic subdivision established by the Saskatchewan Geological Society (1956) and mapped the anhydritic beds in the Tilston, Alida, Frobisher, Midale, Ratcliffe and Poplar "beds" (see Fig. 9). The Poplar Beds locally include beds of halite: the Lower Salt and Upper Salt (Fuller, 1956). The bedded evaporites are truncated by the pre-Jurassic unconformity and Fuzesy (*ibid.*) mapped the various subcrop edges.

The oldest Mississippian evaporite occurs in the Tilston Beds and is a bedded deposit of anhydrite and dolomitic anhydrite. The unit is about 9 m (30 ft) thick in southwestern Manitoba and thins to 1.2 m (4 ft) in southeastern Saskatchewan. It grades laterally, in a westward direction, into a unit of argillaceous limestone and dolostone (Fuzesy, 1960, Fig. 6).

The evaporitic deposit in the Alida Beds was named the Gainsborough Evaporite (Fuller, 1956). It consists mainly of anhydrite and dolomitic anhydrite, but includes interbeds of argillaceous and anhydritic dolostone. The unit has a maximum thickness of 14 m (46 ft) and occurs only locally in southeastern Saskatchewan (Fuzesy, 1960).

The Frobisher Beds include two evaporitic deposits, the Winlaw and Hastings evaporites (Fuzesy, 1969). Both units are interbedded successions of anhydrite, anhydritic dolostone, dolostone, and argillaceous dolostone or limestone. The units grade westward into carbonate rocks. The Winlaw Evaporite has a limited areal distribution in southwestern Manitoba and southeastern Saskatchewan (see Fuzesy, 1960, Fig. 6), and has a maximum thickness of 7.3 m (24 ft). The Hastings Evaporite has a much wider distribution in southeastern Saskatchewan, and reaches a maximum thickness of 31 m (102 ft).

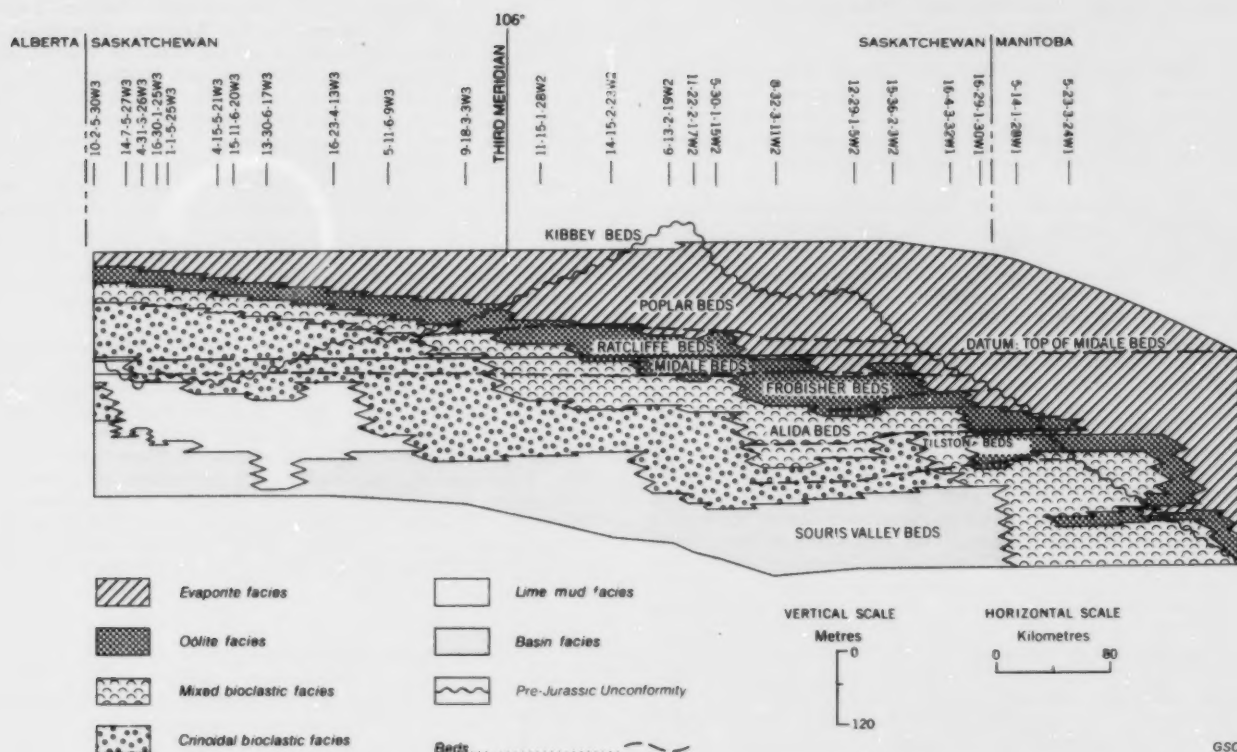


Figure 9. Diagrammatic stratigraphic cross-section of Mississippian strata in Saskatchewan and Manitoba.

The Midale Beds include the Frobisher Evaporite in their lower part. The Frobisher Evaporite is the basal unit of the Charles Formation and is widely distributed in southeastern Saskatchewan and southwestern Manitoba (Fuzesy, 1960, Fig. 7). The evaporitic unit grades westward into carbonates. It has a maximum thickness of 14.3 m (47 ft) and consists of interbedded anhydrite, dolomitic anhydrite, dolostone, and minor argillaceous dolostone or limestone.

The Midale Evaporite (Fuller, 1956) is a basal unit in the Ratcliffe Beds and forms the cap rock in many Saskatchewan oilfields. It is widely distributed in southeastern Saskatchewan and has a maximum thickness of 11.8 m (39 ft). It consists of massive anhydrite interbedded with dolomitic anhydrite, dolostone, argillaceous dolostone and limestone. The thickness and number of carbonate interbeds increase southwestwards toward the depositional edge of the Midale Evaporite.

Two other anhydritic deposits occur locally above the Midale Evaporite in the Ratcliffe Beds. The lower of the two, the Oungre Evaporite, forms the cap rock in the Oungre oilfield. It has a maximum thickness of 7.6 m (25 ft). The upper anhydritic deposit has not been named and is only about 3 m (10 ft) thick.

The Poplar Beds of Fuzesy (1960) are equivalent to the Charles Evaporite of Fuller (1956). They are an interbedded succession of limestone, argillaceous dolostone, anhydrite, dolomitic anhydrite and, locally, halite. The Poplar Beds have a maximum thickness of 135.9 m (446 ft). Complete sections are present only in south-central Saskatchewan near

the International Boundary (see Fuzesy, 1960, Fig. 12). The map unit was subdivided into five informal subunits by Fuller (1956); three of them are evaporites. The presence of leached halite casts in the upper and lower evaporitic subunits prompted Fuller (*ibid.*) to use the names Lower and Upper Salt equivalents. The Upper Salt equivalent includes two salt beds. One of these has a maximum thickness of 12.2 m (40 ft), the other is 4.6 m (15 ft) thick and is known from only one location (see Fuzesy, 1960, p. 39).

The Kibbey Formation of Late Mississippian age (Scott, 1935; Fuzesy, 1960; Macauley et al., 1964) is present only in the extreme southern part of Saskatchewan. The formation includes a lower interbedded member of red sandstone, siltstone, shale, anhydrite, limestone and dolostone, which is about 30.4 m (100 ft) thick. The sandy member is overlain by the so-called "Kibbey Limestone", a unit composed of limestone and dolostone with interbeds of anhydrite, silty dolostone, and argillaceous carbonate.

Paleogeography

The present subsurface distribution of the Mississippian succession is the result of erosion associated with several epeirogenic events. The argillaceous carbonates of the Exshaw and Banff or Bakken and Souris Valley formations are widely distributed and do not show a great deal of change in lithology. In general, the argillaceous rocks are dominant in northwestern Alberta and the carbonate rocks are dominant in southern Saskatchewan (see Macauley, 1964, Fig. 7-7).

The carbonates and anhydritic beds of the middle and upper parts of the Mississippian succession in Saskatchewan and Manitoba are separated from those in southwestern Alberta by an area in which the equivalent strata are absent because of erosion. This region was uplifted during the Pennsylvanian to Jurassic periods and some areas were emergent during Middle Jurassic time (see Springer et al., 1964). This positive tectonic and paleotopographic high area, known as the Sweetgrass Arch, is situated in southwestern Saskatchewan, Montana and southeastern Alberta.

Environment of deposition

Spreng (1953) noted a repetition of limestone and shale in the lower part of the Mississippian succession of the Rocky Mountains. Thick shale units are overlain by intervals of interbedded limestone and shale that grade upward to massive crinoidal limestone beds. Spreng (*ibid.*) described five types of interbedded successions, which he referred to as "cycles". Several "cycles" can be grouped together as a "megacycle".

Illing (1959) noted interbedded successions of shale and limestone overlain by dolostone and anhydrite in the upper part of the Mississippian succession of the Rocky Mountains,

and illustrated the relationship between a general "carbonate sedimentation cycle" and the inferred environment of deposition. The argillaceous beds at the base of the "cycle" were stated to have accumulated in a normal marine environment below wave base; the overlying interbedded unit, composed of argillaceous beds and bioclastic (crinoidal) limestone, was deposited in shallow water near wave base. The peloidal and oolitic beds in the massive limestones were seen as representatives of the intertidal environment; the stromatolitic, bird's-eye and pisolitic beds, together with the dolostone and anhydrite beds, were classified as lagoonal and evaporitic.

Macqueen and Bamber (1968, Fig. 10) worked out the relationship between cycles and depositional environment in more detail, and indicated that the oolitic and bioclastic beds may have formed beach ridges, which restricted the circulation of water in the nearshore environment. The dolomitic and anhydrite beds, which form the top of the sedimentary "cycle", accumulated behind the oolitic and bioclastic barrier. The model proposed by Macqueen and Bamber (see Fig. 10) may be classified as an "upward shoaling" (Wilson, 1975) or progradational sequence.

The interpretation of the environment for the evaporitic deposits in the upper part of the Mississippian succession in the subsurface of Saskatchewan and Manitoba is

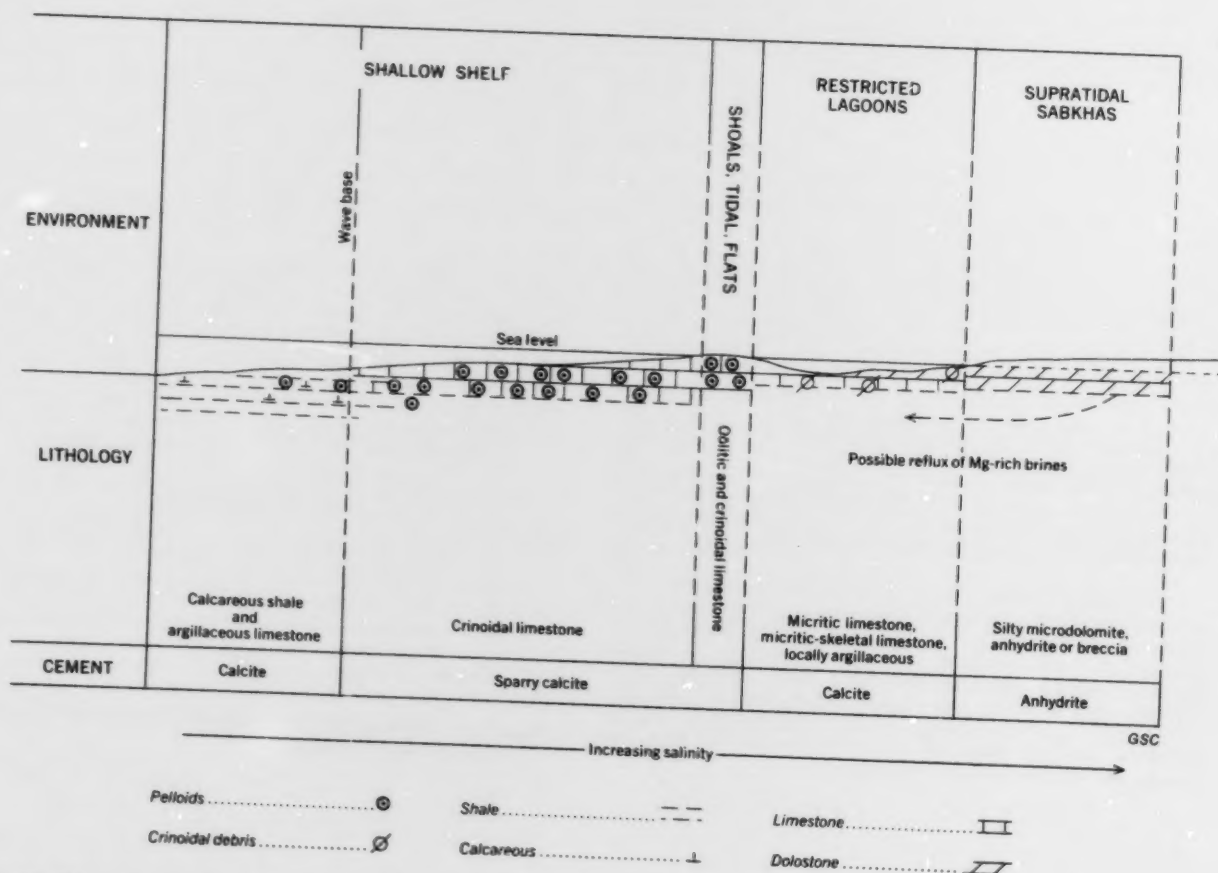


Figure 10. Diagrammatic interpretation of depositional and early diagenetic environments of Mississippian strata (after Macqueen and Bamber, 1968).

similar to that described above (see Fuller, 1956; Edie, 1958; McCabe, 1959; Fuzesy, 1973). Fuller (1956, p. 20) described the four phases of an evaporitic "cycle" as "a thin shale bed at the base (A) overlain by oolitic dolomitic limestone (B), followed by shaly dolomite (C), and finally by anhydrite (D)". He recognized carbonaceous plant fragments in one basal mudstone bed and found "plant rootlet impressions" in the reddish coloured dolostone unit. He interpreted the basal shale bed as a weathered zone (Unit A) which truncates the evaporitic unit D (Fuller, 1956, Fig. 13). The evaporitic succession is thus better described as being "sequential" rather than "cyclic". The term cyclic emphasizes the recurrence of each lithology in a succession of units, but does not suggest the presence of a hiatus. Fuzesy (1973) recognized that the anhydrite includes bedded dolomitic deposits of a sedimentary (lagooal) origin and nodular or nodular-bedded anhydrite of diagenetic (supratidal) origin.

The evaporitic deposits below the pre-Jurassic unconformity may be regarded as a late replacement facies. According to Young and Greggs (1975), the pre-Jurassic period of subaerial erosion produced a variety of vugs. The dolomitization, the filling of the vugs and fractures with anhydrite, and the presence of replacement anhydrite, are related to this period of subaerial exposure. The overlying beds of questionable Jurassic age include evaporites, and it is logical to assume that, during the period of subaerial exposure, the climate was arid and sulphate-rich groundwater moved upward through the Mississippian carbonates, because of excessive evaporation at the surface (see also McCabe, 1959, p. 64). The sulphates precipitated in the shallow subsurface and were subsequently covered by Jurassic sediments.

Structural geology

The Mississippian strata conformably overlie Devonian beds and the structural configuration of both successions is thus similar. In Alberta, both successions are part of the southwestward-dipping homocline. In Saskatchewan and Manitoba, the homocline dips to the south-southwest. This change in the direction of the dip reflects the presence of the Williston Basin. The rate of the dip on the Interior Platform generally increases southerly and southwesterly from about 3.9 to 7.8 m/km (20 to 40 ft/mi.).

The only published regional structural contour map of a Mississippian formation in the region is the map of the Lodgepole Formation in Manitoba (McCabe, 1959, Fig. 21). This map shows several local structural depressions, which are explained by McCabe as collapse features associated with the underground leaching of Devonian salt beds.

The upper contact of the Mississippian succession is an erosional surface. Various Mississippian formations are truncated by this surface. Structural contour maps of the erosional surface, showing the subcrop pattern in North Dakota, Manitoba and southeastern Saskatchewan, were published by Anderson and Nelson (1956, Fig. 6), McCabe (1959, Fig. 15), and Fuzesy (1960, Fig. 3; 1966, Pl. 1). Structural contour maps of individual evaporitic units in Canada are not available at this time.

3. Triassic evaporites

Introduction

In the Interior Plains region, the sedimentary rocks of Triassic age are incompletely preserved and have a limited areal distribution (see Fig. 11). The Triassic succession is much thicker and has a much wider distribution in the Foothills region and in the Rocky Mountains. Evaporitic deposits are present only in the upper part of the Triassic succession of west-central Alberta and northeastern British Columbia.

The Triassic rocks are shelf deposits that accumulated southwest of the ancient landmass, situated somewhere in the Canadian Shield region. They unconformably overlie beds of Permian, Pennsylvanian or Mississippian age (see Barss et al., 1964, Fig. 9-3) and are in turn erosively overlain by

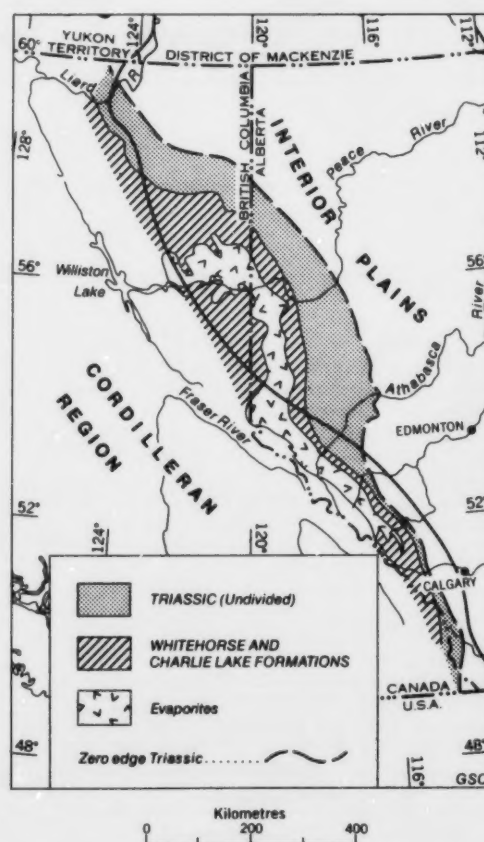


Figure 11. Distribution of Triassic strata and evaporites, western Interior Plains.

Jurassic strata. In the subsurface, the Triassic succession thins gradually to zero from west to east and we find progressively older Triassic beds below the pre-Jurassic unconformity. Complete sections are thus found only in the extreme western part of the Interior Platform. The Triassic succession outcrops in the Foothills region and in the Rocky Mountains.

Stratigraphy

The most complete sections of the Triassic succession are found in the Foothills and the Rocky Mountains of west-central Alberta and northeastern British Columbia. The Triassic rocks in this area were described by McLearn and Kindle (1950) and were subdivided into six informal units. The succession in the nearby subsurface is somewhat different and was subdivided into four formations by Hunt and Ratcliffe (1959). They mapped the Toad-Grayling, the Halfway, Charlie Lake and Baldonnel formations, and noted the presence of evaporitic deposits in the Charlie Lake Formation. Armitage (1962) subsequently recognized the Doig and Montney formations in the subsurface, below the Halfway sandstone.

Evaporitic deposits of Triassic age outcrop in the Rocky Mountains of Jasper National Park and were first described by Allan (1933). These evaporites were placed in the Whitehorse member of the Spray River Formation (Best, 1958), but were later mapped by Gibson (1968a, b and 1974) as the Starlight Evaporite Member of the Whitehorse Formation. Correlations by Gibson (1968a) suggest that the Starlight Evaporite Member is more or less equivalent to the Charlie Lake Formation.

Evaporites of the Charlie Lake and Whitehorse formations

The Charlie Lake Formation was defined by Hunt and Ratcliffe (1959) in the Pacific Fort St. John well. They described the formation from cores as consisting of interbedded sandstone, siltstone, shale, dolostone, anhydrite, and minor limestone. Sandy and silty beds dominate the lower part of the type section; anhydrite and dolostone are prominent in the upper part. The base of the Charlie Lake Formation is sharp and conformable; the upper contact with the Baldonnel Formation is locally transitional. The formation varies in thickness between 0 and 438.9 m (0 and 1440 ft). The facies map and the diagrammatic cross-section shown by Hunt and Ratcliffe (1959) indicate that the Charlie Lake Formation thins in a northeasterly direction, and that the lower part of the formation includes a redbed facies in the east and a sandy facies in the west. The upper part of the formation is dominantly anhydritic. Later work by Barss et al. (1964, figs. 9, 10) suggests that some anhydrite beds are widely distributed and constitute useful subsurface correlation markers. It is thus possible to describe the Charlie Lake Formation in more detail. Roy (1972) has done this on a local scale in the Boundary Lake oilfield.

Equivalents of the Charlie Lake Formation farther south are dominated by sandy dolostone, sandstone and redbeds. They were mapped as the Whitehorse Formation (Best, 1958; Barss et al., 1964; Gibson, 1968a, b, 1974). The Starlight Evaporite Member of the Whitehorse Formation in Jasper National Park includes yellowish and reddish brown weathering carbonates, sandstones, siltstones, intraformational breccia or "solution breccia" and, locally, gypsum (Gibson, 1974). The breccia beds are composed of angular clasts of limestone, dolostone or sandstone, cemented by coarsely crystalline calcite. In Jasper National Park, the evaporitic member varies in thickness between 6 and 402 m (20 and 1320 ft).

The Whitehorse Formation is unconformably overlain by Jurassic beds.

Paleogeography

The Triassic evaporites have a limited areal distribution, and it is difficult to reconstruct the paleogeography without a knowledge of the trends of the major facies changes within the succession. There is a facies change from evaporitic deposits in the east to sandy and carbonate deposits in the west. This facies change occurs somewhere in the subsurface of northeastern British Columbia and probably trends in a northwesterly direction. According to Barss et al. (1964), regional geological evidence suggests that the Upper Triassic evaporites and carbonates are nearshore deposits, which fringed an emergent area of low relief situated in the east.

Environment of deposition

Roy (1972) studied a part of the Charlie Lake Formation in detail. He described the geology of the Boundary Member in the subsurface of northeastern British Columbia. The Boundary Member is a carbonate unit in the Charlie Lake Formation, which varies in thickness between 0 and 10.4 m (0 and 34 ft). The member occurs in the middle of the Charlie Lake Formation and is underlain by a 10 m (33 ft) thick, bedded anhydrite unit. It is overlain with erosional contact by a redbed unit which is at least 15.2 m (50 ft) thick. Detailed correlations of thin marker beds in the subsurface northeast of Fort St. John established the presence of an intraformational unconformity at the top of the Boundary Member, which explains why the member has such a local distribution. Barss et al. (1964) and Roy (*ibid.*) recognized other intraformational unconformities approximately 30 and 60 m below the base of the Boundary Member.

The evaporitic deposits of the Charlie Lake Formation consist of interbedded, commonly distorted, anhydrite and dolostone (Roy, 1972). The anhydritic dolostone is commonly pelletal and locally contains pelecypods. The redbeds are interbedded red and green sandy siltstone and mudstone units that contain minor amounts of anhydrite. The carbonates of

the Boundary Lake Member include microgranular limestone, coquina limestone, pelletal limestone and stromatolitic dolostone. The lithologies of the rocks described above, the interbedded nature, and widespread distribution of the rock units, and the presence of widespread erosional surfaces, suggest that the Charlie Lake Formation was deposited in a variety of nearshore environments.

Structural geology

The evaporitic deposits are bedded and show the same structural configuration as the formational boundaries of the Triassic succession. The regional contour map of the Toad-Grayling Formation of Hunt and Ratcliffe (1959, Fig. 2) shows a southwestward-dipping monocline. The rate of dip is low in the northeast [near the town of Peace River it is about 3.2 m/km (17 ft/mi.)], and gradually increases to about 30.2 m/km (160 ft/mi.) near the eastern boundary of the Foothills region.

In the Peace River area of west-central Alberta, the Paleozoic succession is cut by subvertical faults in the Boundary Lake area. In the downfaulted blocks, Pennsylvanian rocks are preserved, whereas in the uplifted blocks, the pre-Permian erosion has cut deeply into the Mississippian rocks (Naqvi, 1972). The great variation in thickness of the Permian Belloy Formation in the Peace River area suggests the infilling of local paleotopographic depressions or erosional channels; however, these variations in thickness may also be related to a second phase of block faulting. The Triassic beds overlie the Permian Belloy Formation with an erosional contact (Naqvi, 1972), and it is possible that the pre-Triassic paleotopography is highly irregular.

Structural contour maps of the Triassic beds in the Peace River region show high and low anomalies. Some of the anomalies are due to post-Triassic faulting. The Triassic beds in the Boundary Lake oilfield, for instance, occupy an anticline which developed along a steep fault that trends northeast across the north end of the field (Roy, 1972).

4. Evaporites of questionable Jurassic age

Introduction

A unit of redbeds and anhydrite in southern Saskatchewan, northern Montana, North Dakota, and southwestern Manitoba, which conformably underlies marine Jurassic beds, is considered to be Jurassic, although the evaporites are unfossiliferous and may thus be older. The redbeds unconformably overlie Ordovician, Silurian, Devonian, Mississippian and Pennsylvanian strata, and they appear to have filled paleotopographic depressions above the underlying erosional unconformity.

The overlying marine Jurassic beds are much more widely distributed and not only occur in the Williston Basin area but are also present in the western part of the Interior Plains, in the Foothills region, and in the Rocky Mountains (see Fig. 12). Since these beds do not include evaporitic deposits, they are not discussed further by this writer.

Stratigraphy

The redbeds and the overlying unit of anhydrite were mapped in Saskatchewan as the Watrous Formation (Milner and Thomas, 1954) whereas, in Manitoba, equivalent strata were named the Amaranth Formation (Wickenden, 1945; Stott, 1955). In South and North Dakota, similar evaporitic beds are present in the Spearfish Formation (Darton, 1901; Anderson and Nelson, 1956) and in the Gypsum Springs Formation (Imlay, 1947). In the subsurface of Montana, the evaporitic deposits were included in the lower part of the Piper Formation (Peterson, 1958).

In Manitoba, the contact between the Amaranth evaporites and the overlying Reston shale appears to be erosional (Stott, 1955, p. 19). In Saskatchewan, the evaporites are overlain by dark green anhydritic shale of the Gravelbourg Formation.

Evaporites of the Amaranth and Watrous formations

Gypsum and anhydrite are exposed in the vicinity of Gypsumville, northwest of Lake St. Martin, Manitoba, and extensive gypsum deposits occur west of Lake Manitoba near the village of Amaranth (Brownell, 1931; Baillie, 1951; Bannatyne, 1971). In the subsurface, Wickenden (1945) and Stott (1955) mapped these deposits, together with the underlying redbeds, as the Amaranth Formation.

Stott (1955) described a Lower Amaranth unit composed of hard, massive, reddish brown, dolomitic shale with interbeds of orange-pink anhydrite and veinlets of gypsum. The shale grades down to silty and sandy shale and, at the base, there is a fine grained sandstone that overlies a sedimentary breccia composed of dolomitic limestone fragments. In Manitoba, the redbed unit varies between 0 and 39.6 m (0 and 130 ft) and onlaps three paleotopographic high areas (see McCabe, 1959, Fig. 20).

The Upper Amaranth unit (Stott, 1955) overlies the lower unit with a conformable contact. It consists of bluish white, finely crystalline, massive anhydrite, with some interbeds of greenish grey, grey, or dark grey shale and light brown, dense dolostone. In some wells, the redbed facies of the lower unit extends upward into the upper part of the Amaranth Formation and the anhydrite facies is absent. The Upper Amaranth unit thus varies in thickness between 0 and 50.3 m (0 and 165 ft).

The redbeds and overlying anhydritic beds, below the grey marine Jurassic beds in Saskatchewan, comprise the Watrous Formation (Milner and Thomas, 1954). The Watrous is widely distributed in southern Saskatchewan and southeastern Alberta. It thins northward and westward and onlaps a paleotopographic high area in Alberta (Milner and Blacklee, 1958; Klingspor, 1958).

The base of the Watrous Formation is commonly marked by a sandstone or conglomerate bed or by a brecciated, locally cherty unit of anhydrite and shale. In southern Saskatchewan, the redbeds in the lower part of the Watrous Formation are underlain by orange-red sandstone of the Kibbey Formation and the contact is not easily picked (Fuzesy, 1960). Near the northern limit of the formation, the redbeds unconformably overlie evaporitic rocks of Devonian age and the base of the Watrous is equally difficult to determine (Milner and Thomas, 1954).

The rock types in the two members in the Watrous Formation are similar to those of the Amaranth Formation. The Watrous Formation varies in thickness between 0 and 140.2 m (0 and 460 ft) and was mapped by Milner and Thomas (1954, Fig. 2). The lower redbed member was mapped separately in Saskatchewan and Manitoba by Springer, MacDonald, and Crockford (1964, Fig. 10-4) as the lower Watrous member. In southern Saskatchewan, it varies between 0 and 121.9 m (0 and 400 ft) in thickness. North of Regina, the lower member occurs in a separate paleotopographic depression and reaches a thickness of over 60.9 m (200 ft). The two structural cross-sections for Saskatchewan which accompany this report (figs. 29, 34) illustrate the lower member.

Paleogeography

The lower redbed unit of the Amaranth Formation varies greatly in thickness and is absent over several paleotopographic high areas in Manitoba (see McCabe, 1959, Fig. 20). Both redbeds and the anhydritic beds of the Watrous Formation onlap a paleotopographic high area (the Sweetgrass Arch) situated in southwestern Saskatchewan, southwestern Alberta, and northern Montana (see Springer et al., 1964, Fig. 10-4). Peterson (1958) mapped the basal Jurassic Piper Formation and its equivalents in the Interior Plains of Canada and the United States. His isopach map in Figure 3 outlines the ancient Jurassic embayment in Alberta, Saskatchewan, Manitoba, Montana, Wyoming, North Dakota, South Dakota, and Idaho, and indicates the presence of a connection between the Jurassic embayment and the Cordilleran Trough. The Piper Formation is locally absent in central Montana. Peterson outlined several emergent areas in the region which connect the embayment with the trough. According to Peterson, these emergent areas, or islands, restricted the flow of seawater from the Cordilleran Trough into the embayment.

Environment of deposition

Neither the Watrous nor the Amaranth subsurface strata have been studied in detail and little is known about the evaporites. Bannatyne (1971) reported the presence of fusulinid foraminifera in the redbeds below the gypsum deposit at Gypsumville. This indicates that the redbeds may have been deposited in a shallow marine or lagoonal environment. The overlying beds are mainly pure white to translucent, crystalline gypsum, but fine grained, white alabaster and anhydrite beds, partly altered to gypsum, are also present (Davies et al., 1962). The deposit near Amaranth underlies 27 to 30 m (90-100 ft) of glacial drift and includes gypsum and anhydrite. Both deposits are probably extensively recrystallized; however, no detailed studies that clarify the process of formation of these deposits have been published to date.

Structural geology

The Watrous and Amaranth formations overlie an erosional surface and their distribution is related to the paleotopography of the underlying unconformity. Structural contour maps of this surface in Manitoba were presented by Stott (1955, Pl. 9) and McCabe (1959, Fig. 15). It is an

irregular, southwest-dipping surface with local collapse structures associated with the underground dissolution of Devonian salt beds.

The upper contact of the Watrous and Amaranth formations more or less follows the structural configuration of the overlying marine beds of Jurassic age. The structural contour maps published by Francis (1954, Fig. 4) may be used as an example for southern Saskatchewan. In southeastern Saskatchewan, the Jurassic beds dip southward and southeastward toward the centre of the Williston Basin in North Dakota. In southwestern Saskatchewan, the situation is complicated by the presence of a structural high, situated at the International Boundary near Longitude 108° West. This structural high is also evident on the structural contour maps of the top of the Precambrian (see Porter and Fuller, 1959, Fig. 18; Burwash et al., 1964, figs. 2, 3). A similar structure appears under the name Bowdoin Dome on the structural contour map of the Upper Cretaceous Colorado Group of Williams and Burk (1964, figs. 12-15). The Bowdoin Dome may thus be regarded as a Laramide uplift. Both the Jurassic and Cretaceous structural maps show the presence of a low area northwest of the Bowdoin Dome (the "Cobourg Syncline"), and a low area on the northeast side of the dome (the "Moose Jaw Syncline").

The "Moose Jaw Syncline" is not reflected as such on the structural contour map of the Precambrian surface (Burwash et al., 1964), and the reflection of the "Moose Jaw Syncline" on the Jurassic horizon seems to be related to local collapse, which followed the removal by dissolution of Devonian salts from the subsurface (Christopher, 1974).

C. Geology of major evaporitic deposits

The evaporitic deposits of Western Canada that contain salt are described in the next three chapters. The thickness and areal distribution of these salt-bearing deposits are much greater than those of the minor evaporitic deposits (compare figs. 16, 24 with figs. 7, 8, 11, 12). Some of the major evaporitic deposits have been mapped in the subsurface as formations within a group. Others were mapped as members within a formation. The threefold subdivision of the major evaporitic deposits, as used in this report, reflects this situation.

The major evaporitic deposits of Western Canada are those of Cambrian and Devonian age. The Cambrian redbeds and the deposits of anhydrite and halite located in the District of Mackenzie in the Northwest Territories are mapped together in a single formation. The Devonian redbeds and deposits of dolostone, anhydrite, halite and sylvite are divided into two groups. Those of Early and Middle Devonian age are described, together with the interbedded carbonates, as the Elk Point Group. The evaporitic deposits of Late Devonian age are relatively thin and occur only in the southern part of the Interior Plains. They are mapped as members within several formations.

The descriptions of the Cambrian evaporites and the evaporitic deposits of the Elk Point group are partly based on subsurface information collected by the author. The discussion of the Upper Devonian evaporites is entirely based on previously published material.

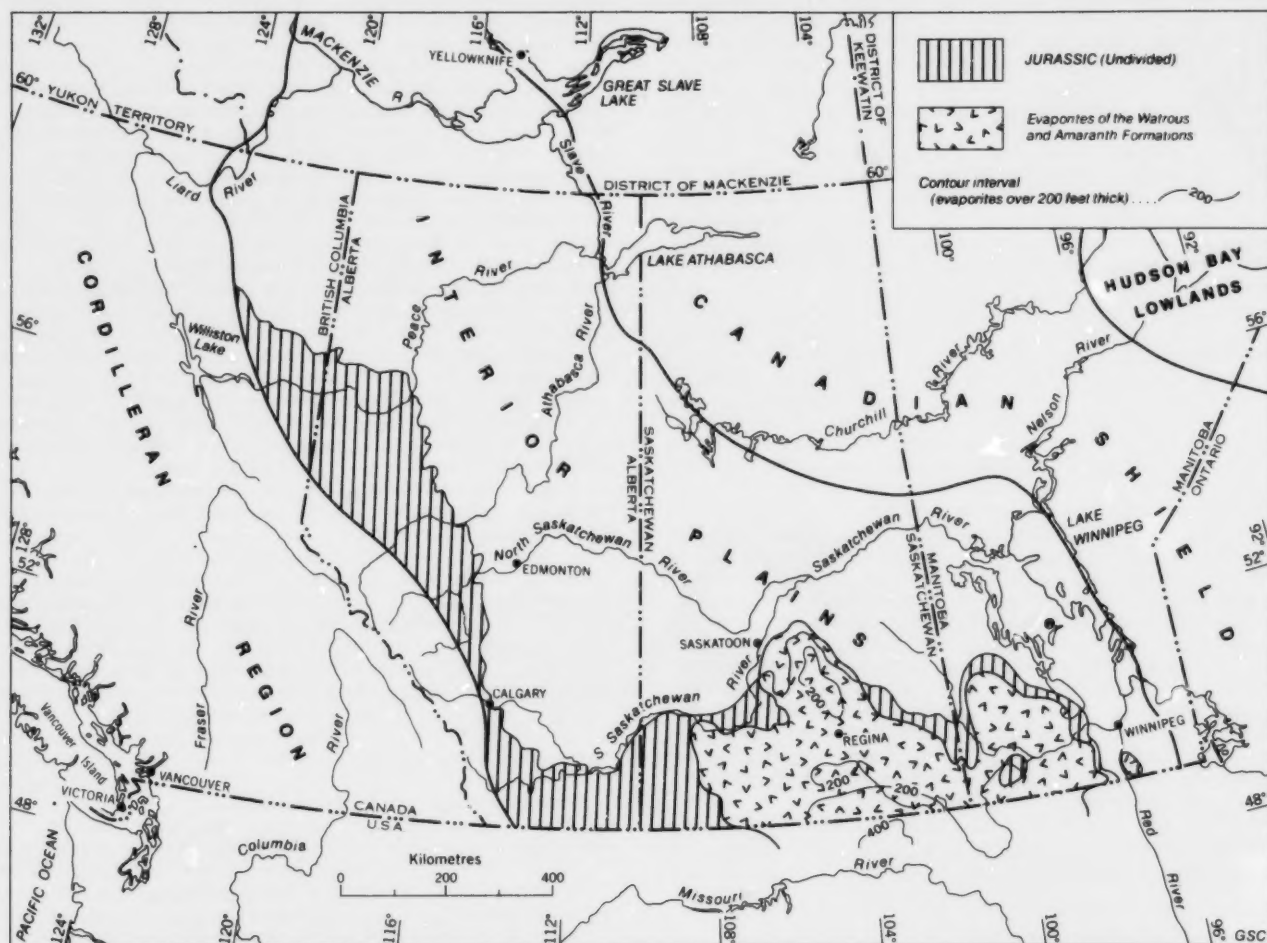


Figure 12. Distribution of Jurassic strata and evaporites of questionable Jurassic age, western Interior Plains.

1. Evaporites of Late Cambrian age

Introduction

Sedimentary rocks of the Cambrian to Lower Ordovician succession are present in the southern and northern part of the Interior Plains area, but are absent in northern Alberta and in the southern part of the District of Mackenzie (see Fig. 13). The stratigraphy of the succession differs in the north and south, with evaporitic deposits occurring only in the north. This suggests that the northern and southern deposits accumulated in distinct subbasins separated from each other by land.

In the southern part of the Interior Plains, Cambrian strata overlie Precambrian granitic rocks similar to those of the Canadian Shield, and the basal Cambrian beds become younger toward the east. The Cambrian to Lower Ordovician succession is unconformably overlain by rocks of Middle Ordovician or Devonian age and, in central Alberta, the succession thins northward to zero because of erosional truncation at the top (see van Hees and North; 1964;

Fig. 3-3). The fact that, in northern Alberta, the Cambrian, Ordovician, and Silurian strata were eroded, suggests that this region was uplifted before the Devonian period.

Because the Cambrian to Lower Ordovician succession in the southern part of the Interior Plains does not include evaporitic deposits, only the succession in the north will be described.

In the northern Interior Plain, the Cambrian succession unconformably overlies sedimentary rocks of Proterozoic age. The unconformity is an irregular paleotopographic surface which has influenced the distribution of the basal Cambrian deposits. It has also been demonstrated that the Lower and Middle Cambrian clastics and the Upper Cambrian evaporitic deposits overlap paleotopographic ridges composed of Proterozoic rocks. Balkwill (1971) described Leith Ridge in the area southeast of Great Bear Lake; Aitken, Macqueen and Usher (1974) recognized the presence of the Mackenzie Arch in the Mackenzie Mountains; and Meijer Drees (1975) mapped the Bulmer Lake Arch in the southern part of the Great Bear Plains. The paleotopographic ridges separated the evaporitic basins from the Cordilleran Trough, and may have acted as barriers to the inflow of fresh seawater, thereby promoting the precipitation of halite.

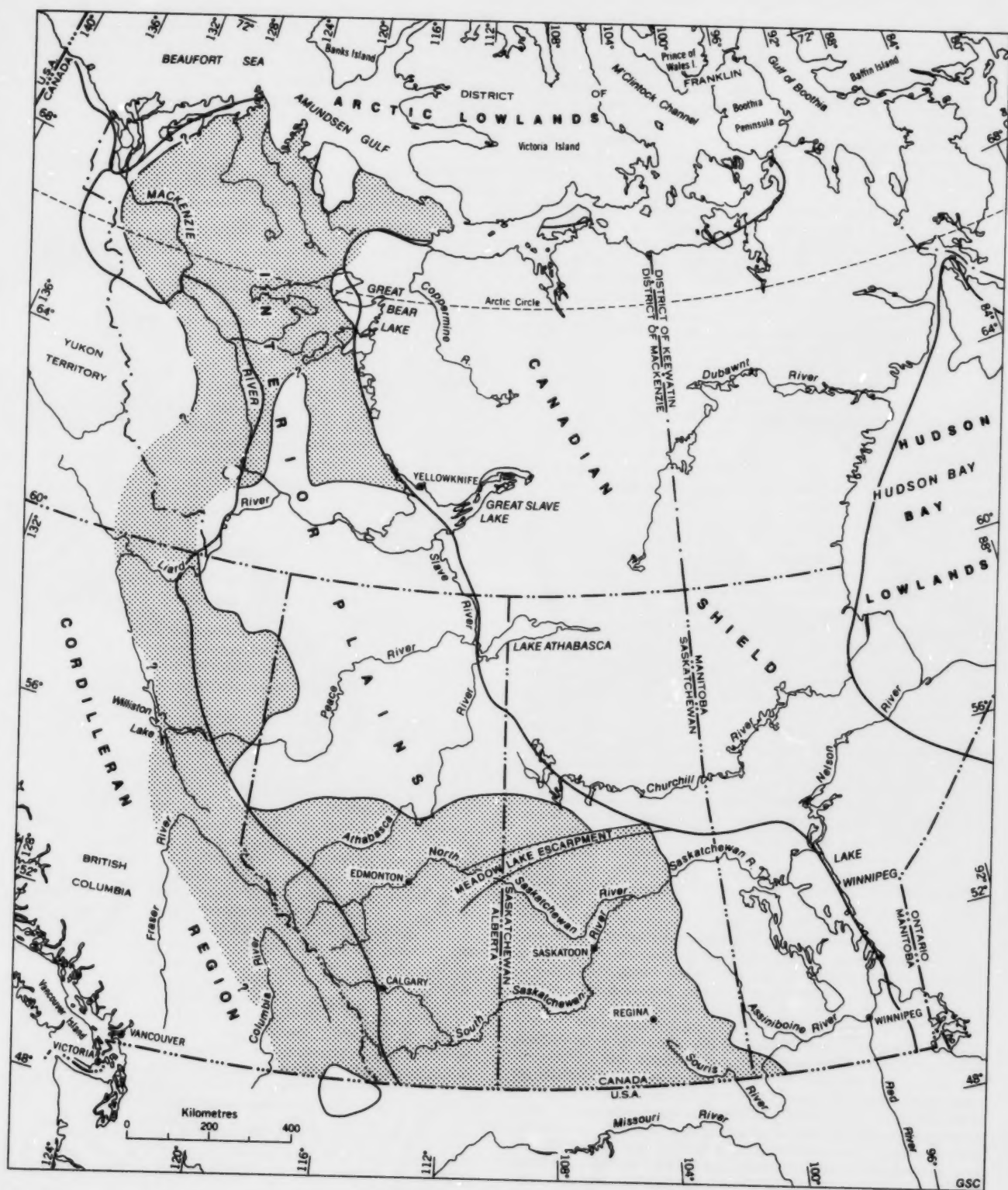


Figure 13. Distribution of Cambrian to Lower Ordovician strata, western Interior Plains.

Only the middle part of the Cambrian to Lower Ordovician succession contains deposits of redbeds, anhydrite, gypsum, and halite. These evaporitic deposits are widely distributed in the Mackenzie and Franklin mountains and the northern Interior Plains. They are, in general, poorly exposed and can be much better studied from subsurface well sections.

The most recent subdivision into formations is shown in Figure 14. In the Mackenzie and Franklin mountains, the basal Cambrian sandstone unit was mapped as the Mount Clark Formation (Williams, 1923; Bell, 1959; Douglas and Norris, 1963). In the eastern part of the Interior Plains, a similar basal sandstone unit was mapped as the Old Fort Island Formation (Norris, 1965; Balkwill, 1971; Cook and Aitken, 1969, 1971; Balkwill and Yorath, 1970). In the Mackenzie Mountains, the basal sandstone unit is overlain by the Mount Cap Formation, an interbedded succession of dolostone, limestone, shale, siltstone and sandstone (Aitken et al., 1974). The Mount Cap Formation in the Great Bear Plain includes glauconitic sandstone, limestone, siltstone and green shale. The formation contains trilobites of late Early to Middle Cambrian age (Aitken et al., 1974). The Mount Cap Formation is poorly exposed in the Franklin Mountains and Great Slave Plain, and was mapped together with the overlying evaporites (Balkwill, 1971; Douglas and Norris, 1963).

The evaporitic deposits of the Saline River Formation have been described from scattered exposures in the Franklin and eastern Mackenzie mountains and from the northern Great Bear and Horton plains (Williams, 1923; Bell, 1959; Aitken et al., 1974; Balkwill and Yorath, 1970; Cook and Aitken, 1969, 1971). They are overlain by the Franklin Mountain Formation, a thick unit of brownish grey, grey, and light brownish grey dolostone with orange-weathering colours (Macqueen, 1970). The Franklin Mountain Formation is generally unfossiliferous and is unconformably overlain by Upper Ordovician to Silurian beds (Norford and Macqueen, 1975). In the southern part of the Great Slave Plain, the Franklin Mountain Formation is thin and, in the outcrop area northwest of Great Slave Lake, the erosional remnants of the Franklin Mountain Formation were mapped together with the underlying Saline River and Mount Cap formations as a single formation (the La Martre Falls Formation of Norris, 1965).

Saline River Formation

Gypsiferous redbeds are sporadically exposed in the eastern Mackenzie and northern Franklin mountains. Williams (1923) described the exposures along Saline River and mapped the redbeds under the name Saline River Formation. The formation was also described by Stelck (in Hume, 1954), Bell (1959), Douglas and Norris (1963), and Aitken, Macqueen, and Usher (1974). According to Aitken (1974, p. 31), it varies in thickness between 0 and 179.8 m (0 and 590 ft) and consists of red and green, gypsiferous shale or mudstone, and pale pink to grey gypsum, interbedded with thin beds of yellowish brown, locally brecciated and stromatolitic dolostone. Units of light grey, fine- to coarse-grained, quartzose sandstone, interbedded with dusky red to green, sandy mudstone or shale, are locally present. Ripple marks and salt crystal casts are commonly seen on the bedding surfaces of these sandy beds.

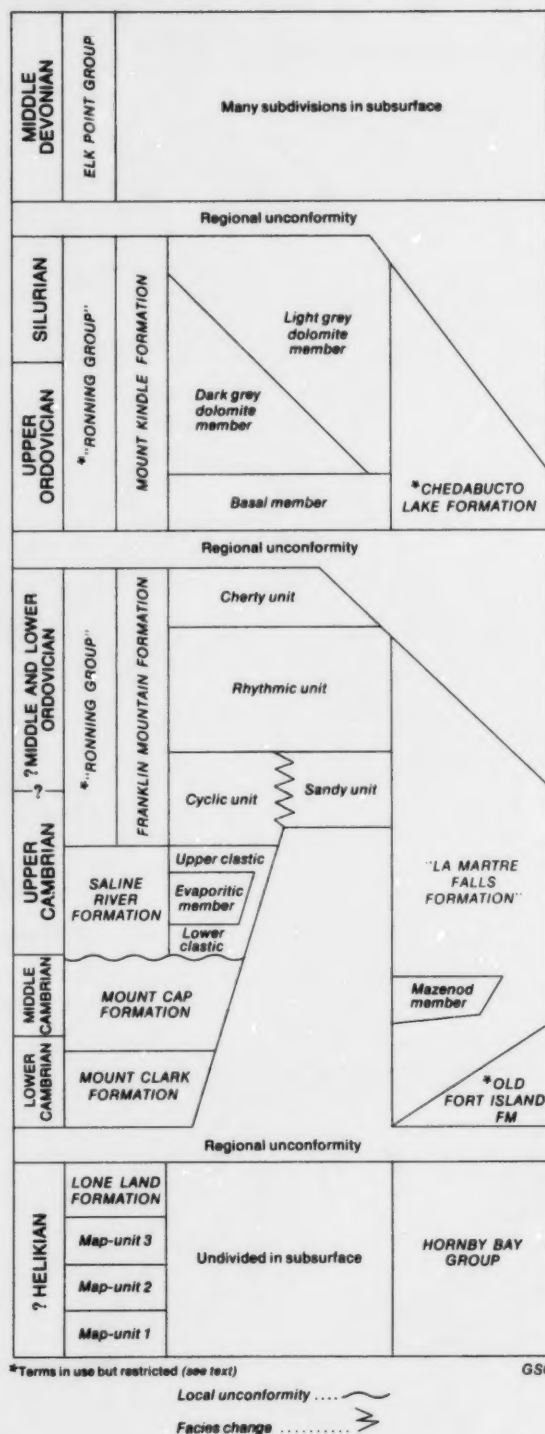


Figure 14. Table of Lower Paleozoic formations, District of Mackenzie.

In the Mackenzie Mountains, the Saline River Formation locally overlies the Mount Cap Formation with a disconformable contact, or directly overlies different units of Proterozoic rocks (Aitken et al., 1974; Aitken and Cook, 1974). The contact with the overlying cyclic unit of the Franklin Mountain Formation is exposed at the type section on Saline River and is conformable (Aitken et al., *ibid.*).

Distribution and thickness. The Saline River Formation outcrops in the northeastern part of the Mackenzie Mountains and in the eastern part of the northern Interior Plains.

Balkwill and Yorath (1970) described the Saline River Formation from outcrops on the Horton Plain. Along the upstream part of Hornaday Canyon, along Hornaday River, the formation is about 36.6 m (120 ft) thick and consists of maroon, green and buff, generally noncalcareous, paper-thin shale, which is thinly interbedded with light greyish green and greenish brown, very finely crystalline dolostone. The dolostone beds are in part gypsiferous and desiccation polygons, salt crystal casts (see Fig. 15c), and ripple marks are common on bedding surfaces. Along Hornaday River, the contact between the Mount Cap and the Saline River formations is structurally conformable and the boundary between the Saline River and Franklin Mountain formations is transitional (Balkwill and Yorath, *ibid.*).

The unit of red and green gypsiferous shale in the Rae River area, near Coppermine, incorrectly mapped as part of the Proterozoic Rae Group by Baragar and Donaldson (1973), belongs to the Saline River Formation (Dixon, 1979).

In the southern part of the Horton Plain and in the northern part of the Great Bear Plain, the Saline River Formation was described from scattered exposures by Cook and Aitken (1969, 1971). Here the formation is about 59.4 m (195 ft) thick, weathers recessively, and consists of green and red shales, with thin interbeds of silty dolostone. Intervals of white and pink gypsum are also present.

Equivalents of the Saline River Formation are very poorly exposed in the Paleozoic outcrop area between Great Slave and Great Bear lakes.

In the subsurface of the northern Interior Plains, the Saline River Formation is intersected by more than forty exploratory oil wells, and there is enough information available to describe the formation in some detail and to draw an isopach map. The formation includes redbeds and salt and varies in thickness. On the isopach map (Fig. 16), it is suggested that there are two subbasins, separated by a paleotopographic ridge that connects the Bulmer Lake Arch with the ridge of Leith Peninsula (see Meijer Drees, 1974). Very little is known about the Saline River Formation in the Lac La Martre area, but in the Colville and Great Bear Lake regions, the formation includes informal Lower clastic, Evaporitic (middle), and Upper clastic members. Along the periphery of this subbasin the Evaporitic member is absent. In the central part of the subbasin, the Saline River Formation, as defined in this report, overlies older Cambrian strata with a transitional contact, but, on the paleotopographic ridges, the formation overlies sedimentary rocks of Proterozoic age with an erosional contact.

The subdivision of the Saline River Formation into three members, and its relationship with the underlying and overlying units in the subsurface of the Colville Hills and

Great Bear Plain, is shown on the stratigraphic cross-section in Figure 17. The contact between the Saline River and the Mount Cap Formation was selected at the base of a fairly distinct shale bed, near the boundary between reddish brown and greenish grey units. This definition of the lower contact is in accordance with that of Aitken et al. (1971) and Meijer Drees (1975). However, Davis and Willott (1978, Fig. 2) used the base of the salt beds as the boundary between the Saline River and Mount Cap formations. This is useful where salt is present but is of no value where salt is absent.

The top of the Saline River Formation in the subsurface is selected near the highest occurrence of red coloured beds. In some cases, the colour change occurs just below the change in lithology from argillaceous dolostone to shale. The transition from dolostone to shale is easily seen on the gamma ray log (see Fig. 17).

The Saline River in the subsurface, as defined above, varies in thickness between 0 and more than 347 m (1138 ft). The thickness of the salt varies between 0 and more than 303 m (994 ft).

The Saline River Formation was completely cored in the Mobil Colville E-15 well (Lat. 67°14'18.2"N, Long. 126°18'25.6"W) and the CDR Tenlen Lake A-73 well (Lat. 67°52'07.5"N, Long. 130°43'21.6"W). The section in the Mobil Colville E-15 well is representative of the facies present in the central part of the basin and includes the Lower clastic, the Evaporitic, and the Upper clastic members (see Fig. 17). The Lower clastic member is relatively thin and includes thinly interbedded and interlaminated, greenish grey, and minor reddish brown, dolomitic shale; light brown, very silty and sandy dolostone, cemented with halite; greenish grey, fine to coarsely crystalline anhydrite and secondary reddish brown halite veins. The base of the Lower clastic member is selected at the base of the lowest occurrence of reddish brown shale at a depth of 1385.9 m (4547 ft)¹, although between depths of 1385.9 and 1394.4 m (4547 and 4576 ft) the underlying strata include thin beds and nodules of secondary anhydrite.

The Evaporitic member of the Saline River Formation in the Mobil Colville E-15 well occurs between depths of 1263.0 and 1375.6 m (4144 and 4513 ft). It is an interbedded succession of light brown to semi-translucent, very coarsely crystalline halite; minor, light grey to semi-translucent, coarsely crystalline halite; light grey, finely to coarsely crystalline nodular anhydrite with stringers and interbeds of brown, halite-cemented, peloidal and pisolitic dolostone; and greenish grey, dolomitic shale (see figs. 15a, d; 18d, f). The greenish grey, dolomitic shale beds are very thinly interbedded and interlaminated with light grey anhydrite; light brown, microcrystalline to very finely crystalline, dolomitic siltstone; and light brown, coarsely- to very coarsely-crystalline halite. The greenish grey shale beds are cut by reddish brown, secondary halite veins.

The Upper clastic member of the Saline River Formation in the Mobil Colville E-15 well is present between depths of 1147.6 and 1263.0 m (3765 and 4144 ft). This section is disturbed by a steeply dipping fault which cuts the core at an approximate depth of 1189 m (3900 ft). Below this fault the beds dip between 60 and 80 degrees. The member consists of a greyish green breccia of dolomitic anhydrite fragments in an anhydrite or shale matrix, and includes reddish brown dusky red, maroon, or greenish grey shale and very light grey, dolomitic siltstone (see Fig. 19h, i).

¹The drill cuttings and cores collected before the introduction of the Metric System are marked in Imperial units. In order to facilitate future reference, the lithological descriptions and the photographs of core samples in this report include a depth indication in feet, unless the original measurements were taken in metric units.

The Saline River section of the CDR Tenlen Lake A-73 well represents the facies which occurs along the periphery of the Great Bear subbasin, and in which the Evaporitic member is absent (see Fig. 17). In this well, the Saline River Formation overlies possible equivalents of the Mount Cap Formation. The correlation in Figure 17 suggests that the unit of anhydritic dolostone between depths of 2287.8 and 2318.6 m (7506 and 7607 ft) is the same unit that is present in the upper part of the Mount Cap Formation of the Iroquois D-40, Manuel Lake J-42, and Colville E-15 wells.

The possible equivalents of the Mount Cap Formation include dark grey, nondolomitic shale; grey green, sandy siltstone; light grey, fine- to coarse-grained sandstone; and greyish green, glauconitic sandstone. The shaly intervals are fairly regularly interlaminated or very thinly interbedded with dolomitic siltstone or silty dolostone. Anhydrite occurs in very thin and thin beds, replacing stromatolitic, oolitic or silty dolostone (see Fig. 18a, b).

The beds assigned to the Saline River Formation in the Tenlen Lake well consist mainly of reddish brown and greyish green dolomitic shale, very thinly interbedded or interlaminated with light grey, silty and anhydritic dolostone. The light grey beds are commonly disturbed by vertical and horizontal burrows (see Fig. 19c); some beds also contain scattered, light-coloured, deformed dolomitic clasts (see Fig. 19d). Also present are scattered erosional surfaces overlain by flat-pebble conglomerates or floatstones. The matrix of these very coarse grained beds is usually replaced by fine to medium crystalline, secondary anhydrite (see Fig. 19a, f).

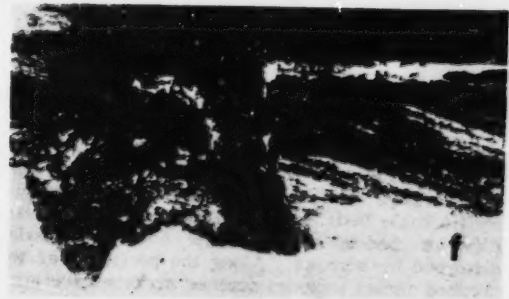
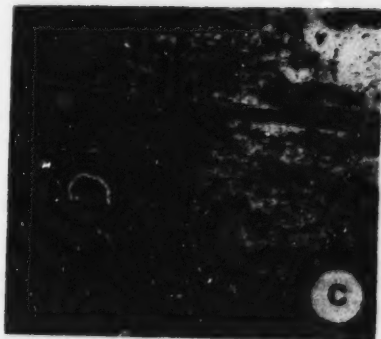
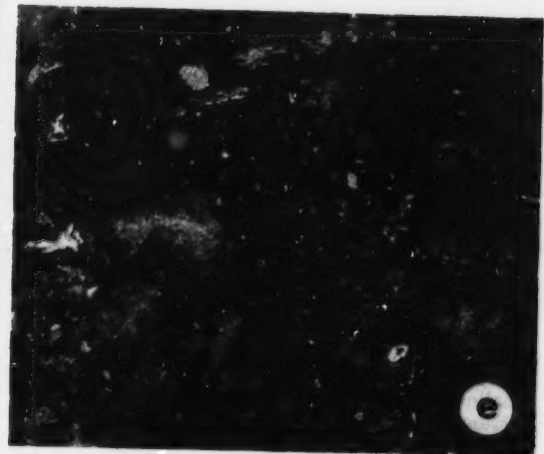
The upper contact of the Saline River Formation in the Tenlen Lake A-73 well is selected at the top of a green, dolomitic shale bed.

The Saline River salt was cored in several other wells, but none of these cores includes a complete section. In the Atlantic et al. Manitou Lake L-61 well (Lat. 66°20'40"N, Long. 128°58'00"W), the Evaporitic member includes brown, semi-translucent, very coarsely crystalline halite with interbeds of light greyish green, dolomitic shale, and reddish brown dolomitic siltstone partly cemented by halite (see Fig. 18h). In the Imperial Loon Creek No. 2 well (Lat. 65°07'20"N, Long. 126°28'51"W), the core consists of brown halite and reddish brown, parallel laminated, and crosslaminated, dolomitic or halitic siltstone (see Fig. 18h). In the Imperial Vermilion Ridge No. 1 well (Lat. 65°07'51"N, Long. 126°05'00"W), the short core in Saline River salt shows brecciation and includes steeply dipping beds. The salt beds in the well are 676.7 m (2220 ft) thick, but this figure does not represent the true thickness. According to Tassonyi (1969), the Saline River salt overlies green shale beds of the Mount Cap Formation. In the Esso Norman Wells 36X well (Lat. 65°17'09.3"N, Long. 126°53'01"W), the Evaporitic member was cored and consists of more than 303 m (994 ft) of clear, brown, and reddish brown, semi-translucent halite, interbedded with green anhydritic shale, reddish brown shale, and light grey, dolomitic siltstone (see figs. 15a, 19g).

Paleogeography. The evaporites and redbeds of the Saline River Formation accumulated in an irregular paleotopographic depression, which was partly filled with marine sediments. The depression was separated from the Cordilleran geosyncline by the Mackenzie Arch. Along the periphery of the depression, the Saline River Formation is represented by a redbed facies whereas, in the central part of the basin, thick deposits of halite occur (see Fig. 20). The southern and western limits of the salt deposits are depositional, the northern limits unknown, and the eastern limit is a dissolution edge (see Fig. 21).

Figure 15. Photographs of Saline River evaporites, salt facies (true to scale, except where indicated).

- a. Core sample of very coarsely crystalline, orange-brown halite with thin, discontinuous interbeds of greenish grey, anhydritic shale. Salt crystals have disrupted the bedding. Esso Norman Wells 36X well; Lat. 65°17'09.3"N, Long. 126°53'01.6"W; depth 1510 m.
- b. Core sample of reddish brown halite with thin, discontinuous, dolomitic shale beds. Basal salt bed is very coarsely crystalline. Salt bed in middle includes fragments of crossbedded shale and siltstone. Upper bed includes dolomitic shale pebbles and anhydrite nodules (see fig. c). Atlantic et al. Manitou Lake L-61 well; Lat. 66°20'40"N, Long. 128°58'00"W, depth approx. 5578 feet (1700.2 m).
- c. Thin section of upper salt bed in figure b. Dark grey dolomitic shale pebbles and grey microcrystalline anhydrite nodules stand out in a reddish brown halite matrix (light grey in photograph). The matrix is composed of small, clear, halite nodules and reddish brown, impure halite "cement".
- d. Core sample of light grey, semi-translucent, coarsely crystalline halite. Mobil Colville E-15 well; Lat. 67°20'18.2"N, Long. 126°18'25.6"W, depth 4398 feet (1340.5 m).
- e. Bedding surface of outcrop sample with "salt hoppers". The photograph shows a cast of the upper surface of a salt bed from which halite crystals were leached and replaced by dolomitic sandstone. La Ronciere Falls, Hornaday River, Horton Plain.
- f. Thin section through "salt hopper" from sample e. The bedding in the crosslaminated sandstone above the "salt hopper" is disturbed by collapse. Sand from above has filled a cavity below. The cavity was once occupied by halite.
- g. Bedding surface of a core sample showing angular ridges and salt crystals. This photograph shows the underside of a salt bed and the ridges outline the former presence of halite crystals. Atlantic et al. Manitou Lake L-61 well; Lat. 66°20'40"N, Long. 128°58'00"W; core 2, box 6.
- h. Scanning electron microscope photograph of contact between halite crystal (right) and silty dolostone (left) of figure g. The halite crystal is partly dissolved and contains several hematite crystals (arrows).



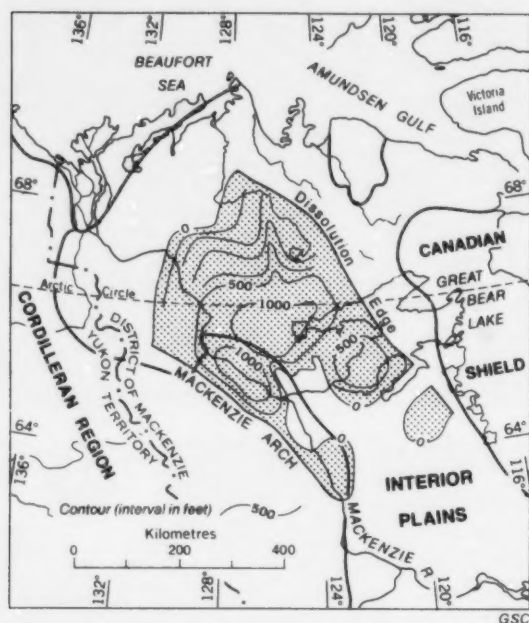


Figure 16. Isopach map, Evaporitic member, Saline River Formation, District of Mackenzie.

Because the Saline River Formation is unfossiliferous and the overlying beds of the Franklin Mountain Formation lack diagnostic fossils, it is not possible to correlate in detail the Saline River evaporites with the marine Cambrian succession in the western part of the Mackenzie Mountains. The relationship between the evaporites and redbeds east of the Mackenzie Arch and the marine deposits west of the Arch are thus unknown, and the paleogeographic situation does not merit elaboration.

Environment of deposition. The Saline River Formation consists of redbeds, anhydrite and halite. The redbeds include very fine grained, silty sandstone and shale beds, which contain delicate sedimentary structures of a lagoonal, shallow water, and semi-restricted environment. The dolomitic shale beds are discontinuously parallel laminated, and the interbedded silty beds are commonly crosslaminated or disturbed by burrows. Along the periphery of the basin, the redbed facies includes scoured surfaces overlain by thin pebble beds and interbeds of oolitic and stromatolitic dolostone. These sediments may be regarded as nearshore, possibly intertidal, deposits.

The remaining evaporites can be subdivided into two groups, known as primary and secondary deposits. Primary deposits precipitated in water either at the sediment-water interface or in the water just below the air-water interface. The secondary evaporitic deposits accumulated from groundwater brines in pre-existing porous sediments during periods of desiccation.

It is probable that the bedded halite is a primary deposit, which accumulated during periods of extreme evaporation and desiccation of the entire Saline River basin. It is possible that the very thin, reddish brown salt beds, composed of very coarse crystals and separated by shale, have grown at, or just below, the sediment-water interface.

The thick, reddish brown salt beds resemble the thin ones because they are composed of similar halite crystals and are also commonly separated from each other by inclusions and thin interbeds of laminated shale (compare figs. 15a, 18f). The halite beds are commonly underlain by silty or shaly beds cemented by halite, suggesting that the accumulation of sediment and the precipitation of halite followed each other closely. The sharp, upper contacts of some salt beds and the collapse structures seen in the overlying sediments (see Fig. 15f) indicate that, in some cases, the accumulation of sediment coincided with an influx of water unsaturated with salt. Thus, the salt accumulated by evaporation from a standing body of water which underwent periods of high and low water levels. The salt is reddish brown and, in places, contains crystals of hematite (see Fig. 15h), suggesting that the environment of deposition was rich in oxygen and, consequently, that the reddish brown salt beds accumulated in very shallow water.

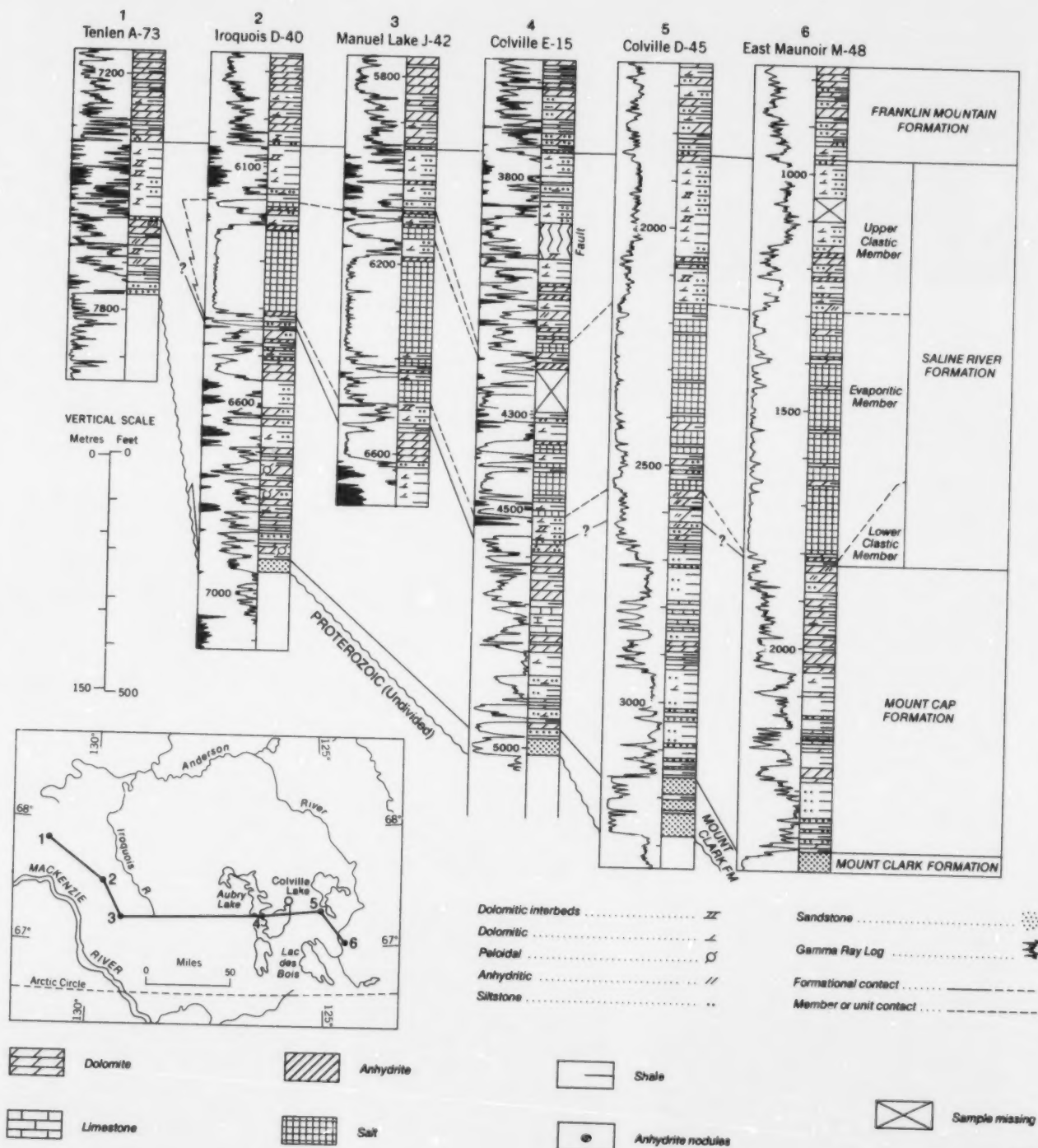
The upper two beds in the sample shown on Figure 15b and c are crossbedded. They include coarse and very coarse shale chips, and consist of clear halite grains cemented by reddish brown halite. These beds must have accumulated in extremely saline, turbulent water.

Secondary deposits of halite occur in the dolomitic siltstone and sandstone. These fine clastic sediments are cemented by halite, and in some beds halite has partly replaced the original dolomite cement (see Fig. 18e, h). In the pisolitic dolostone beds, the halite occurs as a cement but has also partly replaced the pisolites (see Fig. 18d).

Anhydrite is only present as a secondary deposit. It occurs as nodules or beds in reddish brown or greenish grey dolomitic shale, dolomitic siltstone and sandstone, and in oolitic, stromatolitic, and pisolitic dolostone. It is also present in the conglomeratic beds of the nearshore redbed facies. The anhydrite is semi-translucent and fine to medium crystalline. In Figure 18d and g, nodular anhydrite has obliterated the original pisolitic structures. The nodular anhydrite may have accumulated in the shallow subsurface from groundwater brines rich in calcium sulphate, during periods of desiccation. This process is described in more detail by Kinsman (1966) and Butler (1970), from Holocene supratidal sabkhas. A similar process also occurs in saline lakes.

Structural geology. In the Mackenzie and Franklin mountains, the strata are folded and faulted. Broad, flat-topped anticlines are separated by narrow synclines. High- and low-angle thrust faults, rejuvenated antecedent faults, and strike-slip faults occur. The trend of the folds and thrust faults changes from north-south to northwest-southeast (see Fig. 22). The evaporites and redbeds of the Saline River Formation are easily deformed, and it is postulated that they are contorted and brecciated near thrust faults and in faulted anticlines.

In the Interior Plains, the Paleozoic succession is largely undisturbed, and the evaporites of the Saline River Formation dip gently to the southwest (see Fig. 21). In the Colville Hills and western Great Bear Plains, the homoclinal structure is locally disturbed by narrow, faulted anticlines, broad asymmetric folds, fault-related drag folds, and domal structures (see Haimila, 1975 and Davis and Willott, 1978). Steeply-dipping faults are also present (see Fig. 21). The Saline River Formation is affected by these tectonic structures to a much larger degree than the underlying and overlying more competent rock units. It may be that the existence of the Colville Hills structural province is related to the distribution of evaporites in the subsurface (compare figs. 16, 22) because salt is easily deformed.

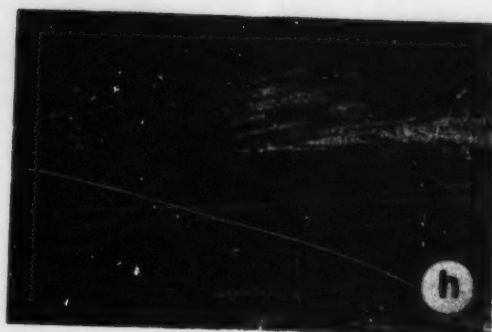
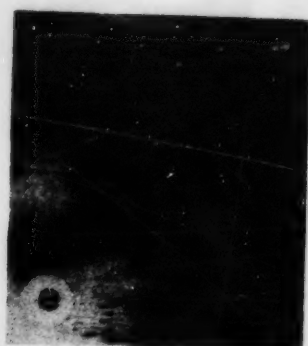


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Figure 17. Stratigraphic cross-section, Cambrian strata, Great Bear Plain, District of Mackenzie.

Figure 18. Thin section photographs of core samples from the Mount Cap and Saline River formations (scale indicated).

- a. Stromatolitic dolostone, Mount Cap Formation; Mobil Colville E-15 well; Lat. 67°20'18.2"N, Long. 126°18'25.6"W; depth 4559 feet (1389.6 m). Dark layers are bituminous; grey layers are microcrystalline dolomite; white layers, patches and veins are very finely crystalline anhydrite.
- b. Oolitic dolostone overlain by dolomitic siltstone, Mount Cap Formation; Mobil Colville E-15 well; depth 4498 feet (1371.0 m). Ooids are dolomitic and partly replaced by anhydrite (white on photograph).
- c. Breccia of algal-crust fragments. Evaporitic member, Saline River Formation; Mobil Colville E-15 well; depth 4498 feet (1371.0 m). White areas are clear halite; light grey areas anhydrite; and dark grey areas dolomite. Note the curled edge on one fragment just above the letter c.
- d. Pisolitic dolostone, partly replaced by halite and nodular anhydrite: Saline River Formation, Evaporitic member; Mobil Colville E-15 well; depth 4345.5 feet (1324.5 m). Dark areas are dolomite; solid white area on right side is anhydrite; white areas in and between pisoliths are halite.
- e. Reddish brown, dolomitic siltstone; Saline River Formation, Evaporitic member; Mobil Colville E-15 well; depth 4497.5 feet (1370.8 m). In the light coloured areas the dolomite cement is replaced by semi-translucent halite.
- f. Very thinly interbedded, greenish grey shale, light grey siltstone and small, clear and reddish brown, displacive halite crystals. Mobil Colville E-15 well; depth 4503 feet (1372.5 m).
- g. Grey, crosslaminated, dolomitic siltstone, partly replaced by light coloured, nodular anhydrite (basal part of sample). In the upper part of the sample, reddish brown halite (black) has partly replaced the dolomite cement of the siltstone. Saline River Formation, Evaporitic member; Atlantic et al. Manitou Lake L-81 well; Lat. 66°20'40"N, Long. 128°58'00"W; core 2, box 4.
- h. Pale reddish brown, crosslaminated, very finely grained sandstone interbedded with reddish brown, dolomitic shale. Sandstone is cemented by halite. Saline River Formation, Upper clastic member; Imperial Loon Creek #2 well; Lat. 65°07'20"N, Long. 126°28'51"W; depth 4772 feet (1454.5 m).

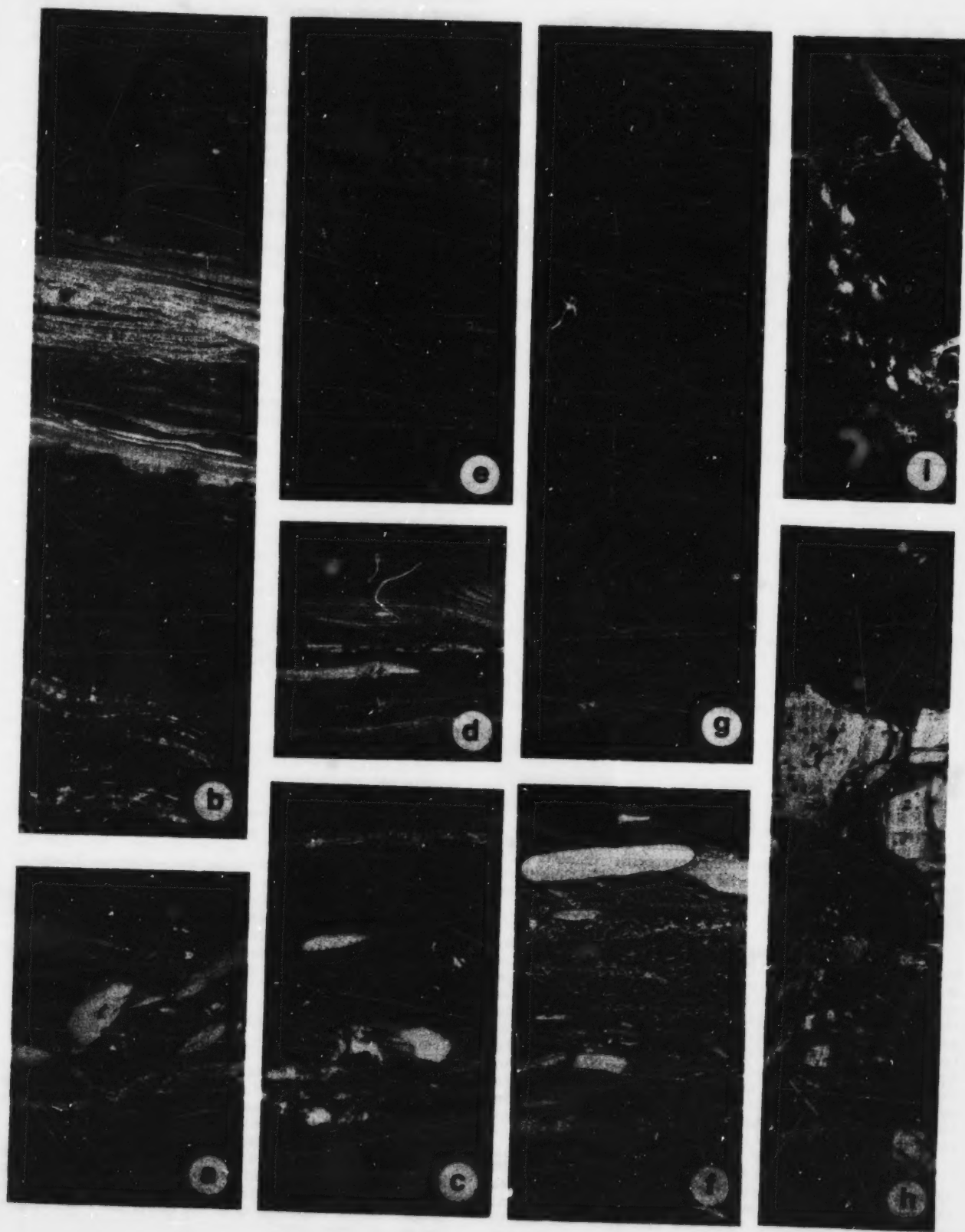


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Figure 19. Core samples of Saline River evaporites, redbed facies (true to scale).

- a. Scoured surface overlain by a conglomerate. Unit underlying the surface is an irregularly interbedded, locally crosslaminated succession of light grey, silty dolostone and greyish brown, very finely grained, anhydritic sandstone. It is cut by a reddish brown, anhydrite veinlet. The conglomerate consists of light grey, silty and sandy dolostone pebbles in a matrix of greyish brown, very finely crystalline anhydrite. Somewhat lighter coloured, finely crystalline anhydrite nodules are present in the matrix. These have an aligned-felted appearance. CDR Tenlen Lake A-73 well; Lat. 67°11'40"N, Long. 129°15"W, depth 7457.5 feet (2273.0 m).
- b. Light brown, stromatolitic dolostone, partly replaced by greyish brown anhydrite (dark areas) is sharply overlain by thinly bedded dolostone, wackestones and mudstones. Dark grey coloured beds are very anhydritic and include lighter coloured, deformed layers and inclusions of dolomite. The light grey, crosslaminated beds are silty dolostone. Note the presence of several scoured surfaces. CDR Tenlen Lake A-73 well; depth 7456 feet (2272.6 m).
- c. Dark reddish brown, dolomitic shale with light grey, somewhat deformed, dolomitic siltstone pebbles and scattered green layers of shale. Individual pebbles and green shale layers are surrounded by pale green halos. CDR Tenlen Lake A-73 well; depth 7412 feet (2259.2 m).
- d. Burrow-like structure in succession of dark reddish brown, dolomitic shale and light brown, dolomitic siltstone. The area surrounding the burrow is pale green, discoloured. CDR Tenlen Lake A-73 well; depth 7387 feet (2251.6 m).
- e. Very regularly interbedded succession of dark reddish brown shale and pale reddish brown, dolomitic siltstone. The siltstone beds contain very fine, partly oxydized pyrite crystals which are surrounded by dark red mottles. Several vertical veinlets of light reddish brown anhydrite are present. CDR Tenlen Lake A-73 well; depth 7382.5 feet (2250.2 m).
- f. Interbedded succession of pale greenish grey, dolomite mudstone and greyish brown, anhydrite floatstone. The mudstone beds are microcrystalline, laminated and contain many scattered, fine, anhydrite crystals. The floatstone beds are a mixture of anhydrite and dolomite. The matrix of these beds is very finely to finely crystalline anhydrite; the light coloured grains and pebbles are dolomite. CDR Tenlen Lake A-73 well; depth 7400 feet (2255.5 m).
- g. Sample is typical of many clastic interbeds present in the salt facies. It consists of reddish brown and green mottled shale and light grey and reddish brown mottled dolomitic siltstone. Basal part of sample is mainly siltstone and includes scattered, coarse to very coarse mudstone grains. In the reddish brown mottles (dark areas), the dolomite cement is replaced by halite. Remainder of sample is mainly green shale, but includes reddish brown, laminated siltstone lenses cemented by halite. Several, large, orange-brown (dark), anhedral to subhedral halite crystals are present in central part of sample. Esso Norman Wells 36x well; Lat. 65°17'09.3"N, Long. 126°53'01.6"W; depth 1520.5 m.
- h. Breccia composed of light coloured fragments of laminated, microcrystalline dolostone, and matrix of greenish grey dolomitic shale, partly replaced by yellowish brown, very finely to finely crystalline anhydrite (dark in photograph). Upper clastic member; Mobil Colville E-15 well; Lat. 67°14'18.2"N, Long. 126°18'25.6"W; depth 4021 feet (1225.6 m).
- i. Steeply dipping and fractured, banded succession of light brown and grey, regularly laminated, very anhydritic, dolomite-mudstone. In some beds the dolomite is partly replaced by halite. Open fractures are filled with clear (white) or orange (dark) halite. Evaporitic member; Mobil Colville E-15 well; depth 4317 feet (1315.8 m).



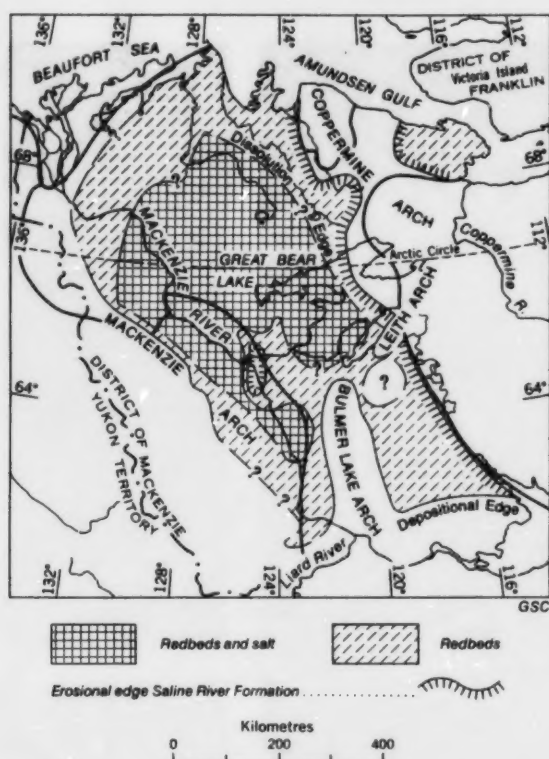


Figure 20. Paleogeography and facies of the Saline River Formation, District of Mackenzie.

2. Evaporites of Early and Middle Devonian age

Introduction

Rocks of possible Early Devonian age, which include evaporites, are discontinuously present in the Interior Plains and in the northern part of the Cordilleran Orogen. Rocks of Middle Devonian age containing evaporitic deposits are widely distributed in the Interior Plains, but in the Cordillera they are only present locally in the southeastern part of the Rocky Mountains.

The Early and Middle Devonian part of the Devonian succession of the Interior Plains is dominated by evaporitic deposits. These deposits and their stratigraphic equivalents were included by Belyea (1952) in the Elk Point Group. In the Interior Plains, the deposits of the Elk Point Group overlies rocks of Precambrian to Silurian age with an erosional contact (see Fig. 6). The Elk Point Group is overlain by Upper Devonian beds, except in the area near the Canadian Shield, where the group is exposed or unconformably overlain by Cretaceous beds. Most of the evaporitic deposits have been leached from the shallow subsurface and they do not reach the outcrop area.

In the subsurface of the Interior Plains, the evaporitic deposits are interbedded with carbonates, and lateral facies changes occur between redbeds and deposits of anhydrite, dolostone, and limestone. Here, the succession includes, in the middle part, a widespread unit of fossiliferous carbonate

rocks (the Winnipegosis Formation and its equivalents), which contains a Middle Devonian fauna of late Eifelian to early Givetian age. The base of this unit divides the Elk Point Group into lower and upper "subgroups" (see Grayston et al., 1964).

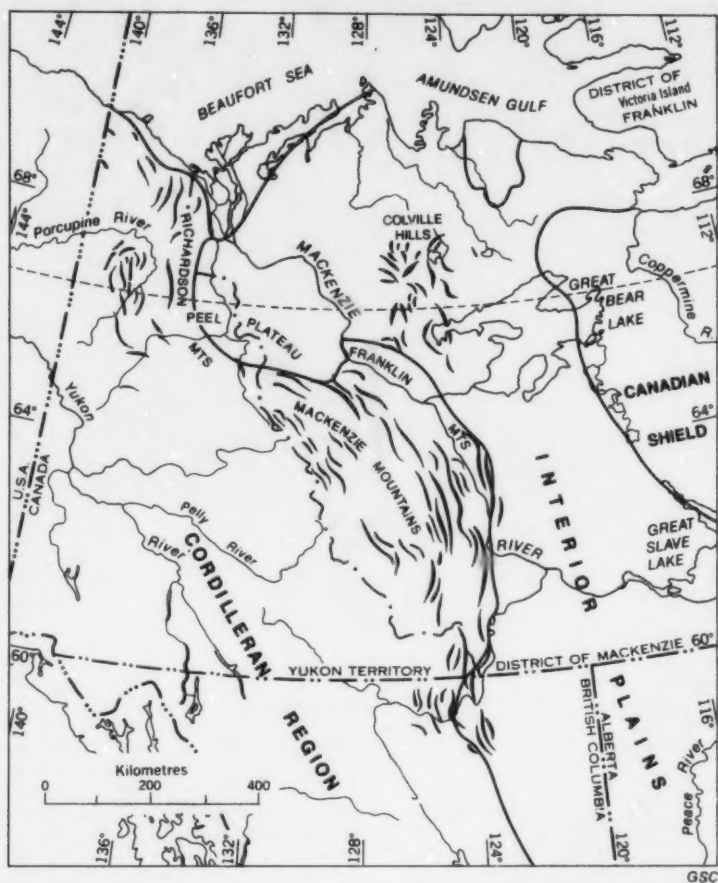
The lower Elk Point evaporites accumulated in several paleotopographic depressions on the pre-Devonian surface, and include redbeds, anhydrite, and halite, with minor interbeds of dolostone. These paleotopographic depressions were regarded as subbasins of the Elk Point Basin (Grayston et al., 1964, figs. 5-11A; Holter, 1969, Fig. 5; Bebout and Maiklem, 1973, Fig. 28). The subbasins are shown schematically in the table of Middle Devonian formations (Fig. 23).

In the southern Mackenzie Mountains, the Devonian succession overlies rocks of Silurian age (Douglas and Norris, 1963) and includes beds of Early Devonian age. In the southern part of the District of Mackenzie, the basal Devonian beds are younger and the basal contact is erosional. Farther south, in Alberta and Saskatchewan, and illustrated in Figure 23, the Lower Elk Point subgroup includes beds of Early Devonian age. There is thus evidence available to regard the Lower Elk Point subgroup as a transgressive succession of evaporitic rocks. The distribution and thickness of the subgroup are directly related to the pre-Devonian paleotopography.

The carbonates and evaporites of the Upper Elk Point subgroup are widely distributed in the Interior Plains, but are thin or absent in western Alberta and west-central Alberta. Apparently, this area remained largely emergent during the Middle Devonian and acted as a source of detrital sediment. The thickness and distribution of the Upper Elk Point subgroup is thus related to pre-Devonian paleotopography, but Figure 23 shows that there were also other factors which influenced the thickness of the subgroup and the distribution of the evaporitic deposits. In the southern Mackenzie Mountains and the Upper Mackenzie River area, the Givetian Stage is only represented by a thin unit, of limited distribution, consisting of argillaceous beds, or by isolated reefal mounds of limestone. In the southern part of the District of Mackenzie and in northeastern British Columbia, the Givetian Stage is represented by reefal beds and associated carbonate rocks. Farther south, in northern Alberta, these carbonates grade into a succession of interbedded dolostone and anhydrite and, in Saskatchewan, the Givetian Stage is represented by an equally thick succession dominated by halite. Evidence from the regional distribution of the different facies suggests that the evaporites accumulated in an embayment (the Elk Point Basin), which was separated from the Mackenzie Trough by a carbonate facies. This facies restricted the inflow of seawater to the south. Conditions in the ancient Elk Point embayment must have been very stable during the Eifelian and Givetian stages, because the evaporitic units can be mapped over large distances across the Interior Plains without much variation in thickness or lithology.

Distribution and thickness

The Elk Point Group was mapped by Grayston et al. (1964) in the southern part of the Interior Plains. The succession is present in southwestern Manitoba, in southern Saskatchewan, in southeastern and northern Alberta, in northeastern British Columbia, and in the southern part of the District of Mackenzie (see Fig. 24). Equivalents of the lower part of the Elk Point Group are present in the northern Interior Plains and in the Cordillera. These have been mapped on the isopach map of the Lower Elk Point subgroup and are discussed later.



Major tectonic boundaries Fold

Figure 22. Structural geology, District of Mackenzie.

In the southern part of the Interior Plains, the Elk Point Group is more than 457.2 m (1500 ft) thick in east-central Alberta and northeastern British Columbia, and the maximum thickness is a little more than 304.8 m (1000 ft) in southern Saskatchewan and in the southern part of the District of Mackenzie. These variations in thickness are due to the irregularities of the pre-Devonian paleotopography. The thinning toward the southwest is due to depositional onlap and the southwestern zero-edge marks the depositional limit of the Elk Point Basin. The thinning toward the northeast is due, in part, to leaching of salt in the shallow subsurface and to erosional truncation in the Paleozoic outcrop area southwest of the Canadian Shield.

The Elk Point Group extends southward across northeastern Montana and North Dakota (Sandberg, 1961), where it varies in thickness between 0 and 182.8 m (0 and 600 ft).

Stratigraphy

The term Elk Point Formation was introduced by McGehee (1949) to describe the thick succession of evaporitic deposits in the subsurface of east-central Alberta between

pre-Devonian rocks and the Upper Devonian Waterways Formation. No type section was designated. These evaporitic beds were first described in the Fort McMurray area by Allan (1943). Belyea (1952, 1959) subdivided the Elk Point Formation into several unnamed units and raised the Elk Point to group status. Crickmay (1954) selected the succession in the Anglo-Canadian Elk Point No. 11 well (located in Lsd. 2, Sec. 21, Tw. 57, Rge. 5, west of the 4th meridian) as the type section, and defined the top of the Elk Point at the top of the highest occurrence of reddish coloured shale. He and Mitchell (1951) recognized that the Elk Point Group includes stratigraphic equivalents of the Winnipegosis and Elm Point formations, described earlier by Tyrrell (1892) and Kindle (1914) from the Manitoba outcrop area. In 1953, for the first time, Baillie subdivided the Elk Point Group of Saskatchewan and Manitoba into formations; because of a miscorrelation, between two red shale units, however, the top of the Elk Point Group was selected at the base of the Dawson Bay Formation (see Grayston et al., 1964). Sherwin (1962) introduced formational names for map units in the Lower Elk Point subgroup, and Norris (1963) named some map units in the outcrop area of northwestern Saskatchewan and northeastern Alberta. Subsequent work in the subsurface of Alberta and Saskatchewan by Grayston et al. (1964) established a stratigraphic framework for the Elk Point Group in the southern part of the Interior Plains, and this subdivision is used here with minor alterations. In this subdivision, the Dawson Bay Formation and the overlying "First Red Bed" unit are included with the Elk Point Group (see Fig. 23).

The Lower Elk Point subgroup includes, in ascending order, the "Basal Red Beds" units, and the Lotsberg, Ernestina Lake, Cold Lake, and Contact Rapids formations. Equivalent beds of the Contact Rapids Formation in Saskatchewan and Manitoba overlie rocks of Ordovician and Silurian age with an erosional contact. These beds were named the Ashern Formation (Baillie, 1950, 1953). In northern Alberta, the Cold Lake Formation is overlain by anhydrite and redbeds of the Chinchaga Formation (Law, 1955). In the southern part of the District of Mackenzie (Northwest Territories), the Lower Elk Point subgroup includes the Mirage Point and Chinchaga formations (Law, 1971).

Equivalents of the Lower Elk Point subgroup are present in the Cordilleran Orogen and Interior Platform of northeastern British Columbia and southern District of Mackenzie. They are the Delorme (in part), the Camsell, Sombre, Arnica, Manetoe, Landry, Headless, Bear Rock, and Stone formations (see Fig. 23). Other equivalents occur locally as the Cedared and Burnais formations in southeastern British Columbia and in the southern Rocky Mountains.

The Upper Elk Point subgroup includes a widespread fossiliferous carbonate unit at the base. This unit was mapped as the Winnipegosis Formation in Saskatchewan and Manitoba (Baillie, 1953; Walker, 1957; Jones, 1963; Holter, 1969; Reinson and Wardlaw, 1972) and in Alberta (Sherwin, 1962; Grayston et al., 1964 and Hamilton, 1971). In the outcrop area of northeastern Alberta, the name Methy Formation was used for equivalent rocks (Nauess, 1950; Greiner, 1956; and Norris, 1963). The term Keg River Formation, introduced by Law (1955) in northern Alberta,

may be regarded as a synonym of the Winnipegosis Formation. In the District of Mackenzie, the upper part of the Nahanni Formation (Douglas and Norris, 1960, 1961, 1963; Noble and Ferguson, 1971) is correlative with the Winnipegosis Formation.

The upper part of the Hume Formation (Bassett, 1961; Tassonyi, 1969), the lower part of the Pine Point, and the Lonely Bay and Horn Plateau formations (Belyea and Norris, 1962; Norris, 1965) all occupy a stratigraphic level similar to that of the Winnipegosis Formation (see Fig. 23).

The strata overlying the fossiliferous carbonates of Late Eifelian age vary greatly in lithology. They include, from north to south (left to right on Fig. 23), dark shale (the Spence River Formation), dark limestone, and marl (Bituminous shale and limestone member of the Pine Point Formation), interbedded anhydrite and dolostone (The Muskeg Formation), and interbedded anhydrite and halite (The Prairie Evaporite Formation).

Figure 23 indicates that in the Lower Mackenzie River area, the Bituminous shale and limestone member of the Pine Point Formation is locally thin or absent because of extreme condensation or nondeposition. The Nahanni and Lonely Bay formations are, in places, sharply overlain by dark grey, silty shales containing Late Devonian conodonts (Gunther and Meijer Drees, 1977; Meijer Drees, in press), and beds equivalent to the Upper Elk Point evaporites are thin or absent. In places, the Nahanni and Lonely Bay formations are overlain by reefal carbonates of the Horn Plateau Formation. These reef mounds contain Givetian fossils (McLaren and Norris, 1964). Studies by Vopni and Lerbekmo (1972), and Fuller and Pollock (1972) indicate that the scattered reef mounds suffered from submarine and subaerial erosion. Fuller and Pollock (1972) concluded that there was a period of nondeposition during the Late Givetian Stage in which sea level fell and the reef mounds were exposed. This period is schematically shown as a hiatus in Figure 23. Griffin (1965, Fig. 2) also postulated the local presence of a hiatus below the black shale unit, at the base of the Upper Devonian shales, in the area west of the Presqu'ile Barrier, in northeastern British Columbia. This black shale unit is known as the Muskwa Formation (Gray and Kassube, 1963).

In the extreme southern part of the District of Mackenzie, the Pine Point Formation is overlain by argillaceous and fossiliferous limestone of the Sulphur Point Formation, which is, in part, replaced by a white, vuggy, coarsely crystalline dolostone (the Presqu'ile Formation). The porous dolostone and the fossiliferous limestone locally include reefal beds, and it has been argued that at one time these formations formed the Presqu'ile Barrier Reef (Law, 1955; Grayston et al., 1964). The Sulphur Point Formation extends southward into northern Alberta and northeastern British Columbia (Belyea and Norris, 1962; Belyea, 1971). In northern Alberta, the Sulphur Point Formation thins toward the south and is replaced from the base upward by finely crystalline dolostone. The finely crystalline dolostone, in turn, is replaced by an interbedded succession of dolostone and anhydrite (the Muskeg Formation). This facies change is schematically shown in Figure 23.

It is also evident from Figure 23 that the upper part of the Muskeg Formation is stratigraphically equivalent to the Dawson Bay Formation of Saskatchewan and Manitoba (see Grayston et al., 1964). However, a number of geologists working in Saskatchewan and Manitoba (Walker, 1959; Lane, 1959, 1964; Holter, 1969; Sandberg and Hammond, 1958; Sandberg, 1961; Gorell and Alderman, 1968; McCabe, 1967; Christopher et al., 1971; Norris et al., 1982; and Dunn, 1982) have incorrectly excluded the Dawson Bay Formation from

the Elk Point Group, following the example of Baillie (1953), who selected the top of the Elk Point Group as the top of the Prairie Evaporite Formation.

The top of the Elk Point Group is picked at the highest occurrence of reddish shale in the Anglo Canadian Elk Point No. 11 well. The basinwide correlations by Grayston et al. (1964), Klingpor (1969), and Hamilton (1971) indicate that this red shale unit is in mappable continuity with the Watt Mountain Formation in northern Alberta, and with the basal shale member of the Souris River Formation in Saskatchewan (the "First Red Bed" unit of Fig. 23).

Because the succession of the Elk Point Group includes several mappable, evaporitic units, each containing redbeds, anhydrite and halite, the subdivision into a lower and upper subgroup is useful. In the following discussion, the evaporitic deposits of the Elk Point Group and its equivalents are subdivided into Lower and Upper Elk Point subgroups.

Lower Elk Point and equivalent evaporites

The Lower Elk Point subgroup may be described as a succession of redbeds which, in the lower part, includes several units of halite or anhydrite and, in the upper part, a facies transition from redbeds to interbedded anhydrite and shale. The thickness and distribution of the interbedded halite and redbeds in the lower division is dependent on the paleotopography of the pre-Devonian unconformity.

The lower division accumulated in three paleotopographic depressions situated in central Alberta, northern Alberta, and the District of Mackenzie. Paleotopographic high areas such as the Western Alberta Ridge, Prairie Plateau, Peace River Arch, Tathlina Uplift and Keele Arch, separated some of the subbasins from each other (see Fig. 25). The upper division of the Lower Elk Point subgroup is widely distributed in the southern Interior Plains, and overlies the lower division in the paleotopographic depressions, or overlies the pre-Devonian unconformity on the paleotopographic highs (see Fig. 23 and figs. 26-34). Crickmay (1954) recognized nine unnamed members in the Lower Elk Point subgroup of the Anglo Canadian Elk Point No. 11 well (the type section of the Elk Point Group). These included three salt beds. This subdivision follows lithological boundaries and was used by Belyea (1959) to describe the geology of the Elk Point Group in central and southern Alberta.

The subdivision of the Lower Elk Point subgroup into formations proposed by Sherwin (1962) and used by Grayston et al. (1964) is only partly based on lithological boundaries. Two of Sherwin's formations (the Lotsberg and Cold Lake formations) are combinations of salt beds and red shale units. Near the depositional edge of these formations, the salt beds disappear but the red shale units persist beyond the depositional limits of the salt beds and are mapped as part of the "Basal Red Beds" unit. In the area southwest of the Paleozoic outcrop belt near the Canadian Shield, the salt beds are leached from the subsurface and all the red shale units are also part of the informal "Basal Red Beds" unit. It is now known that the upper part of the Ernestina Lake Formation, consisting of dolostone and anhydrite, is a very useful marker, on the basis of which one can separate redbeds equivalent to the Lotsberg Formation from redbeds equivalent to the Cold Lake Formation.

Sherwin (*ibid.*) did not define the boundaries between the "Basal Red Beds" unit and the redbeds of the Contact Rapids and Ashern formations and this limits the usefulness

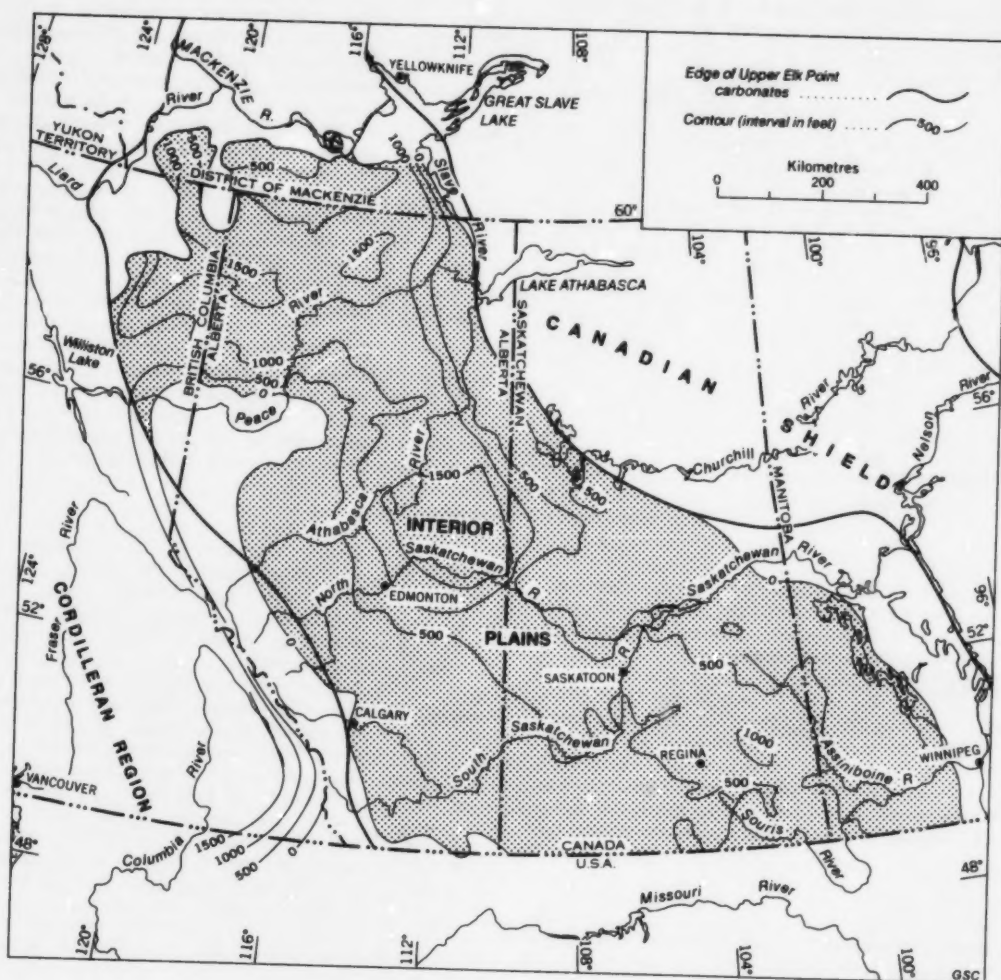


Figure 24. Isopach map, Elk Point Group, western Interior Plains.

of the "Basal Red Beds" as a map unit. The nomenclature would have been less complicated if the redbeds had been defined as a formation and the individual salt beds as members.

The subdivision of the Lower Elk Point equivalents, used by Douglas and Norris (1963), Tassonyi (1969) and Law (1971) in the northern Interior Plains and Mackenzie Mountains, is presently under review (Meijer Drees, in press). Correlation between the Bear Rock and Camsell outcrop sections and their equivalents in the subsurface is hampered by the fact that, in the shallow subsurface, salt is leached from the section and anhydrite is replaced by gypsum. The result is collapse and widespread brecciation of the intervening and overlying carbonates and redbeds. It is thus impossible to recognize subsurface map units composed of evaporites in the surface section.

Because of the nomenclature and correlation problems mentioned above, it is difficult to discuss all the previously described evaporitic map units in strict ascending order. The sequence by which these map units are discussed below is thus somewhat arbitrary. The discussion includes the

evaporitic deposits of the Camsell Formation and its equivalents in the subsurface; the "Basal Red Beds" unit; the Lotsberg, Ernestina Lake, Cold Lake and Mirage Point formations; the Bear Rock Formation and its equivalents in the subsurface; the Contact Rapids, Ashern, Chinchaga and Stone formations, and the Meadow Lake Beds. The correlation, stratigraphic position and approximate age of these map units are shown in Figure 23.

Camsell Formation. The name Camsell Formation was proposed by Douglas and Norris (1963) for a succession of limestone and dolostone in the southern Mackenzie Mountains that is commonly brecciated, either devoid of bedding or thickly bedded. Breccia fragments vary in size from a few centimetres to several metres and are angular to subrounded. The breccia matrix is mainly calcite, which partly forms a fine stockwork; it locally includes large salt casts. The formation weathers light grey with light brown, yellow and orange. On Rouge Range, the Camsell Formation is 563.8 m (1850 ft) and on Redstone Range it is 518.1 m (1700 ft) thick (see Fig. 35). The formation is underlain by the Delorme and overlain by the Arnica Formation (Douglas and Norris, 1963).

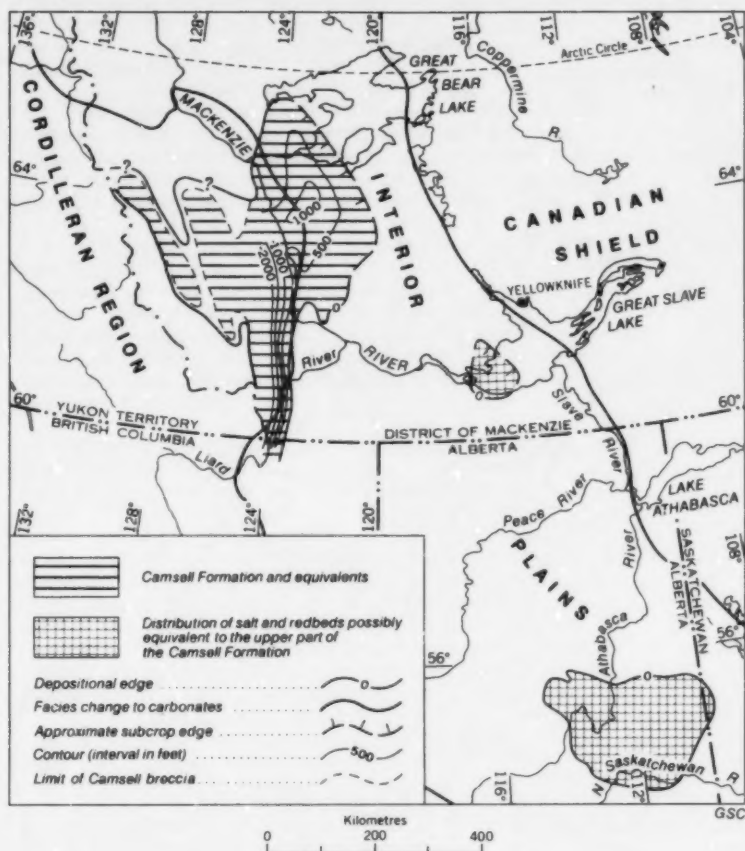


Figure 35. Isopach map of the Camsell Formation and its subsurface equivalents, District of Mackenzie.

On Tundra Ridge, the Camsell formation is composed of a colour-banded, yellow weathering sequence of peritidal, sandy carbonates up to 3609 feet (1100 m) thick (Morrow, 1984).

In the subsurface of the southern Mackenzie Mountains, stratigraphic equivalents of the Camsell Formation consist of interbedded dolostone, anhydritic dolostone, silty dolostone, dolomitic sandstone and anhydrite. The dominant lithology is a greenish grey, cryptocrystalline dolostone containing much siliceous clay. This dolostone is interbedded with pale, sandy dolostone, and red dolomitic shale beds are locally present.

Because the upper and lower boundaries of the Camsell Formation are based on the weathering features of the formation and were not studied in detail by Douglas and Norris (1963), it is not possible to define the formation in the three wells that did penetrate equivalents of the Camsell Formation. The three wells are the Pan Am A-1 Mattson Creek No. 1 well (Lat. $61^{\circ}02'28''N$, Long. $123^{\circ}48'30''W$), the F.P.C. Tenneco Root River 1-60 well (Lat. $62^{\circ}39'32.21''N$, Long. $123^{\circ}24'28.96''W$), and the Shell West Wrigley G-70 well (Lat. $63^{\circ}98'17''N$, Long. $124^{\circ}11'50''W$).

In the subsurface of the northern Interior Plains, evaporitic beds partly equivalent to the Camsell Formation are present between the Silurian-Ordovician Mount Kindle Formation below, and the Early or early Middle Devonian Evaporitic member of the Bear Rock Formation or the Arnica Formation above. This interval was mapped by Williams (1975, Fig. 7.1) and consists of interbedded dolostone, anhydritic dolostone, dolomitic shale, sandy dolostone and anhydrite. The interval is light grey, pale greenish grey and reddish brown, and is marked at the top by a widely distributed unit of sandy dolostone (Meijer Drees, in press). The evaporitic succession overlies paleotopographic high areas in the Great Slave and Great Bear plains (see Fig. 35) and, near the depositional margin, the anhydritic interbeds are thin or absent. Here, the dolostone beds contain much silt and sand-sized quartz. The thickness of the evaporitic succession in the southern part of the Great Bear Plain is up to 304.8 m (1000 ft).

"Basal Red Beds" Unit. The term "Red beds" was used by Cameron (1922) to describe a succession of shale, gypsum, anhydrite, and salt in the Northwest Windy Point No. 1 well located on the northwest of Great Slave Lake in the District of Mackenzie (Lat. $61^{\circ}19'N$, Long. $115^{\circ}52'W$). At this location, the evaporites unconformably overlie Precambrian granite and are overlain by the Chinchaga Formation (the Fitzgerald Formation of Cameron). Cameron (*ibid.*) assumed that these evaporites were Silurian. Law (1955) used the term "rocks of doubtful age" for the succession of interbedded pink, reddish brown, brown and white, partly dolomitic anhydrite; reddish brown dolomitic or calcareous shale; yellowish grey to reddish brown dolostone; and red or green shale, siltstone, and sandstone, which, in northern Alberta, occurs between Precambrian granitic rocks and anhydrite of the Chinchaga Formation. Law (*ibid.*) correlated them with the "Red beds" in the Windy Point No. 1 well.

In central Alberta, Sherwin (1962) introduced the term "Basal Red Beds" to describe a subsurface unit of greenish grey, fine- to coarse-grained, quartzose sandstone; red, sandy shale; and brick-red, dolomitic or calcareous, silty shale. The "Basal Red Beds" unit unconformably overlies Cambrian rocks in the Canadian Seaboard Ernestina Lake well, located in Alberta (Lsd. 10, Sec. 13, Tw. 60, Rge. 4, west of the 4th meridian). In the Ernestina Lake well, the redbeds are overlain by halite of the Lotsberg Formation (see Fig. 33). Elsewhere, the unit is overlain by the Ernestina Lake or the Cold Lake formations and unconformably overlies Precambrian granitic rocks. In places where the Cold Lake salt and the Ernestina Lake dolostone are absent, the "Basal Red Beds" unit underlies the Contact Rapids or the Chinchaga Formation. The "Basal Red Beds" unit thus includes the salt-free, nearshore equivalents of all the higher formational units of the Lower Elk Point subgroup and is equivalent to the redbeds of doubtful age which underlie the Chinchaga Formation. The boundary between the Contact Rapids Formation and the "Basal Red Beds" unit was not defined, although in a later paper (Grayston et al., 1964, figs. 5-10) the term Grizzly sandstone was used for sandy equivalents of the Contact Rapids Formation. Thus, one may argue that over paleotopographic high areas where the Ernestina Lake dolostone is missing, the "Basal Red Beds" unit merges with the Contact Rapids Formation (see Fig. 23).

Because the "Basal Red Beds" unit includes basal Devonian sandstone beds, it is possible to group all basal Devonian sandstone beds of the lower Elk Point subgroup below the Chinchaga or Contact Rapids formations within the "Basal Red Beds". The basal Devonian sandstone beds, from exposures along the Slave River in northeastern Alberta described by Norris (1963) as the La Loche Formation and the informal Grizzly sandstone, are thus part of the "Basal Red Beds" unit. The basal Devonian sandstone and redbeds, mapped by Belyea (1971) as "Basal beds" in the subsurface of the southern District of Mackenzie and northern Alberta, may also be grouped with the "Basal Red Beds" unit. These "Basal beds" onlap and overlap the Tathlina Uplift, a pre-Devonian paleotopographic high area in the southern part of the District of Mackenzie. They locally underlie the Keg River Formation (Belyea, 1971, Fig. 3).

Because the boundaries of the "Basal Red Beds" unit are poorly defined, the redbeds cannot be mapped as a separate unit. However, the distribution of the unit should closely follow the distribution of the lower Elk Point subgroup shown in Figure 25. Sherwin (1962) reports a thickness of 72.5 m (238 ft) in the Ernestina Lake well and, according to him, the unit varies in thickness between 0 and 91.4 m (0 and 300 ft).

Lotsberg Formation. In the paleotopographic depression of east-central Alberta (the central Alberta subbasin), the "Basal Red Beds" unit is, in places, overlain by a massive unit of halite, or by an interbedded unit of halite and redbeds for which Sherwin (1962) proposed the name Lotsberg Formation. The boundary between the "Basal Red Beds" unit and the Lotsberg Formation is a facies change. Near the depositional edge of the Lotsberg, the halite thins to zero and the formation passes into the "Basal Red Beds" unit (see Fig. 33). The northeastern limit of the Lotsberg Formation is a dissolution edge (Sherwin, 1962).

In the type section (the Canadian Seaboard Ernestina Lake well located in Alberta, Lsd. 10, Sec. 13, Tw. 60, Rge. 4, west of the 4th meridian), the formation is 167.6 m (550 ft) thick and consists of almost pure halite.

The salt beds of the Lotsberg Formation were mapped by Hamilton (1971). He recognized a Lower Lotsberg Salt and an Upper Lotsberg Salt separated by an unnamed interval of red shales up to 60.9 m (200 ft) thick. The isopachous maps of the Lower and Upper Lotsberg salts in figures 36 and 37 were redrawn from Hamilton (1971, figs. 6, 7).

The Lower Lotsberg Salt varies in thickness between 0 and 60.9 m (200 ft) and is not affected by dissolution along the northeastern edge. The salt was cored in one well, Imperial Grosmont No. 1, located in Alberta (Lsd. 13, Sec. 17, Tw. 67, Rge. 23, west of the 4th meridian), and was described by Hamilton (*op. cit.*, p. 9) as composed of clear, commonly reddish tinted, very coarsely crystalline halite, containing variable amounts of red shale between the crystals. Shale is also present as discontinuous interbeds, but these and other non-salt interbeds are rare. Anhydrite and dolostone are not present as interbeds.

The Upper Lotsberg Salt varies in thickness between 0 and 152.4 m (500 ft). The northeastern edge of the salt is not depositional but is due to underground dissolution along the northeastern limit. The salt was cored in several wells, listed by Hamilton (*op. cit.*, p. 46), and a completely cored section is available in the Anglo Home C & E Elk Point No. 2 well, located in Alberta (Lsd. 3, Sec. 14, Tw. 57, Rge. 6, west of the 4th meridian), between depths 114.9 and 127.2 m (377.1 and 417.3 ft). According to Hamilton (*op. cit.*, p. 10) the Upper Lotsberg Salt consists chiefly of clear, commonly

colourless, pink or amber, very coarse crystalline halite (see Fig. 38a). Some crystals are up to 15 cm across. Red shale occurs between the halite crystals or as interbeds generally less than 1.5 m (5 ft) thick. Interbeds of anhydrite and dolostone are absent.

The Upper Lotsberg Salt overlaps all but the extreme northwestern tip of the Lower Lotsberg Salt (see figs. 36, 37). Where the two are superimposed, an intervening unit of red shale is present, but, in the areas where the upper salt overlaps the lower salt, this shale unit grades into the "Basal Red Beds" unit.

Both the Lower and Upper Lotsberg Salt members are shown on structural cross-sections A₃-A₄, D₁-D₂ and E₁-E₂ (figs. 28, 32, 33). In Figure 28, the Lotsberg Formation abuts a pre-Devonian paleotopographic high area, the Saskatchewan Plateau (Grayston et al., 1964). The northwestern edge of the Saskatchewan Plateau was named the Meadow Lake Escarpment (van Hees, 1958; Grayston et al., 1964). In figures 32 and 33, the dissolution edge of the Upper Lotsberg Salt member is shown schematically. The leaching of the salt from the shallow subsurface has resulted in collapse of the overlying beds.

Ernestina Lake Formation. In the Canadian Seaboard Ernestina Lake well (see Fig. 33), the Ernestina Lake Formation (Sherwin, 1962) overlies the Lotsberg Salt and includes three members. A basal, red, dolomitic shale unit, 3.6 m (12 ft) thick; a middle, anhydritic limestone unit containing ostracodes, 10.3 m (34 ft) thick; and an upper anhydrite bed, 5.8 m (19 ft) thick. According to Sherwin (1962), the threefold subdivision of the Ernestina Lake Formation is only present in the area where the formation is underlain by Lotsberg Salt. If the Lotsberg Salt is absent, the basal red shale unit is mapped together with the "Basal Red Beds" unit and this affects the thickness of the map unit (see Sherwin, *ibid.*, Fig. 2).

The limestone and anhydrite beds of the Ernestina Lake Formation form a widespread marker in the subsurface of northern Alberta, northeastern British Columbia, and the southern part of the District of Mackenzie. The formation has been traced across central and northern Alberta on structural cross-sections (figs. 27, 28, 32, 33), and has been traced into northeastern British Columbia on cross-section C₁-C₂ (Fig. 31). On structural cross-sections A₁-A₂ (Fig. 26) and B₁-B₂ (Fig. 30), the equivalents of the Ernestina Lake Formation are shown as a thin, unnamed unit of anhydrite below the Cold Lake Salt. The sections show that the Ernestina Lake Formation in northern Alberta and northeastern British Columbia is a fairly continuous unit and locally overlies basal Devonian sandstone beds. The upper Ernestina Lake beds are a useful subsurface map unit in the area just southwest of the Devonian outcrop belt, where the underlying and overlying salt beds have been leached.

Information from the subsurface sections that supplement the report of Norris (1963) suggest that an equivalent of the upper part of the Ernestina Lake Formation is present in the Fort McMurray area of east-central Alberta (see Fig. 39) in the following wells: the Weymann No. 1 well (Sec. 16, Tw. 89, Rge. 3, west of the 4th meridian) between depths of 118.8 and 121.9 m (390 and 400 ft); in the Bear Rodeo No. 1 well (Lsd. 8, Sec. 20, Tw. 89, Rge. 9, west of the 4th meridian) between depths of 334.5 and 337.1 m (1097.5 and 1106 ft); in the Bear Vampire No. 1 well (Lsd. 7, Sec. 28, Tw. 87, Rge. 12, west of the 4th meridian) between depths of 693.4 and 696.8 m (2275 and 2286 ft); in the Bear Biltmore No. 1 well (Lsd. 7, Sec. 11, Tw. 87, Rge. 17, west of the 4th meridian) between depths of 852.4 and 858.0 m

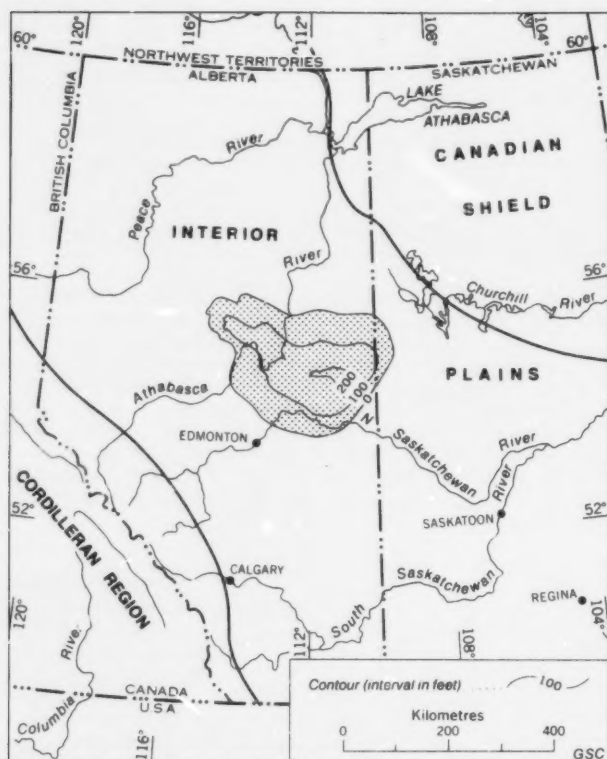


Figure 36. Isopach map, Lower Lotsberg Salt, central Alberta.

(2796.5 and 2815 ft); and in the H.B. Fort Vermilion No. 1 well (Lsd. 15, Sec. 32, Tw. 104, Rge. 8, west of the 5th meridian) between 1094.2 and 1106.4 m (3590 and 3630 ft).

Beds partly equivalent to the Ernestina Lake Formation are exposed in northeastern Alberta along the Slave River. The exposed beds were described by Cameron (1918), Norris (1963), Richmond (1965) and Craig et al. (1967) as the Fitzgerald Formation. Along Slave River, the beds directly overlie a basal Devonian sandstone unit, the La Loche Formation. Here the Ernestina Lake equivalent ranges in thickness between 1.5 and 9.8 m (5 and 32 ft) and consists of interbedded light brown and brown limestone, dolomitic limestone and dolostone. The basal part of the section locally includes a basal unit of sandy dolostone. The beds are sparsely fossiliferous and contain corals, brachiopods, gastropods and ostracodes (see Norris, 1963; Richmond, 1965 and Craig et al., 1967).

In the subsurface of northern Alberta and the southern District of Mackenzie, the Ernestina Lake Formation consists of a yellowish brown, very finely crystalline, locally porous dolostone containing anhydrite-filled vugs. Interbeds of light grey, nodular anhydrite are also present (Belyea, 1971). In the subsurface of the Great Slave Plain, equivalents of the Ernestina Lake can be recognized in the Mirage Point Formation below the Cold Lake Salt member (see Fig. 40). The succession of interbedded dolostone, anhydrite and minor shale includes three sedimentary sequences, consisting of a basal greenish grey shale bed; a brown, thinly bedded and laminated, locally fossiliferous dolostone; and an upper unit

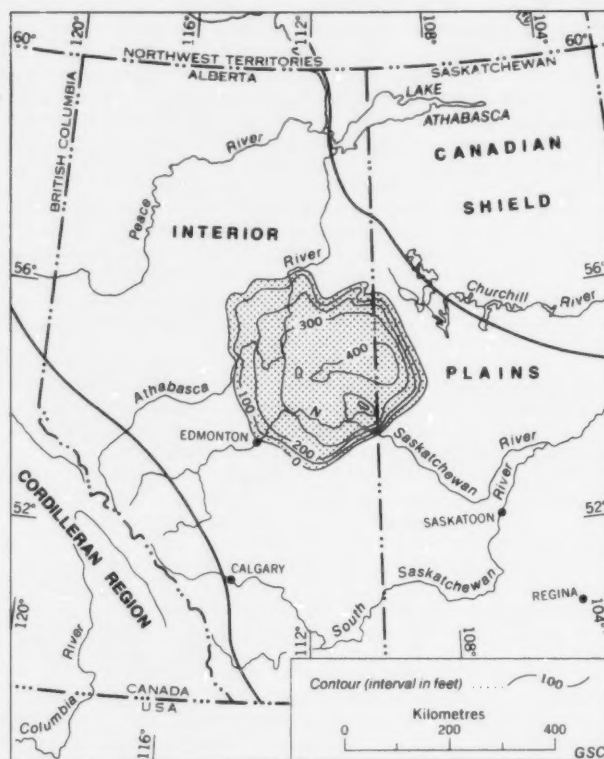


Figure 37. Isopach map, Upper Lotsberg Salt, central Alberta and western Saskatchewan.

of pale coloured, nodular-bedded anhydrite (Meijer Drees, in press). Rice (1967) described the equivalents of the Ernestina Lake in the subsurface of the Great Slave Lake region under the name Fitzgerald Formation, and reported the presence of a diagnostic fauna characterized by the coral *Planetophyllum planetum* Crickmay and the ostracode *Welleria meadowlakensis* Kesling and Takayi. *Planetophyllum* sp. is also present in the Ernestina Lake equivalent of the Mirage Point Formation (Meijer Drees, in press). *Welleria* sp. is present in the limestone bed of the Ernestina Lake Formation in the Ernestina Lake well (Sherwin, 1962), and its presence in equivalents of the Ernestina Lake Formation in the Meadow Lake Beds of west-central Saskatchewan was reported by van Hees (1958).

The areal distribution and thickness of the Ernestina Lake Formation were not mapped, but the distribution of the formation falls within the limits of the Lower Elk Point subgroup. The thickness of the formation varies between 0 and 19.8 m (0 and 65 ft).

Hamilton (1971, p. 11) reported the presence of an anomalous situation in the Triad Berny well, located in Lsd. 6, Sec. 25, Tw. 66, Rge. 16, west of the 4th meridian. In this well, the stratigraphic equivalent of the Ernestina Lake Formation consists of salt. The salt is in mappable continuity with the underlying Upper Lotsberg Salt member. Hamilton (1971, Fig. 8) has mapped the Ernestina Lake salt as part of the Cold Lake Formation. In Figure 41, the anomalous section of the Berny well is compared with the normal sections in two nearby wells, and it is evident that the thin

salt bed at the top of the Cold Lake Formation, in the two nearby wells, is also present in the Berny well. This salt bed is light reddish brown. In the Berny well, it overlies a light grey salt bed that appears to have replaced the Ernestina Lake Formation and the lower part of the Basal shale member of the Cold Lake Formation.

Cold Lake Formation. The Cold Lake Formation was defined by Sherwin (1962) in the Canadian Seaboard Ernestina Lake well. It overlies the Ernestina Lake Formation and consists of two members. The Lower member is 6.0 m (20 ft) thick and consists of red, calcareous shale. The Upper member is 49.7 m (163 ft) thick and consists of salt. The Salt member correlates with Member 5 of Crickmay (1954) and with the "Second Salt" of Govett (1961). The Cold Lake salt member is overlain by redbeds of the Contact Rapids Formation.

Beyond the depositional limit of the Upper salt member, the Cold Lake Formation loses its identity. Grayston et al. (1964, figs. 5-10) mapped the shaly equivalents of the Cold Lake together with the overlying Contact Rapids Formation. This procedure is followed on the structural cross-sections in figures 27, 28, 32, and 33. The contact between the Cold Lake Formation and the Contact Rapids Formation, therefore, is probably a facies boundary.

The Cold Lake Formation is present in east-central and northern Alberta and in northeastern British Columbia. Equivalents of the Salt member have been mapped in the southern part of the Mackenzie District as the Cold Lake salt member of the Mirage Point Formation (see figs. 26, 30). In east-central Alberta, the Cold Lake salt member varies in thickness between 0 and 49.6 m (163 ft). In northern Alberta and northeastern British Columbia, the salt is between 0 and 76.2 m (250 ft) thick. The isopach map of the Cold Lake salt (Fig. 42) indicates the presence of two separate salt deposits. The Cold Lake salt in east-central Alberta is separated from the salt deposit in northern Alberta by a paleotopographic high area, which is part of the Peace River Arch. The isopach map suggests that there is a possible connection between the Cold Lake salt in northern Alberta and the Cold Lake salt member of the Mirage Point Formation in the District of Mackenzie, where the salt varies in thickness between 0 and 117 m (384 ft).

All limits of the Cold Lake salt in Figure 42, except the northeastern edge in Alberta and the northeastern and northwestern edges in the District of Mackenzie, are depositional. They are the result of onlap against paleotopographic high areas. The northeastern edge in Alberta and the District of Mackenzie is due to leaching. The dissolution of salt in the subsurface has resulted in the collapse of the overlying beds. This is evident from the structural cross-sections in figures 30 to 33). The northwestern limit of the Cold Lake salt in the subsurface of the District of Mackenzie is due to a facies change to anhydrite (see figs. 26, 30). This facies change is discussed in more detail in the description of the Mirage Point Formation.

The lithology of the Cold Lake Formation does not show much variation. The basal red shale unit is almost always present and is absent only in the subsurface of Horn Plateau (District of Mackenzie) where the Salt member overlies greyish, bedded anhydrite or brown dolostone.

The Cold Lake salt member was cored in several wells. In Alberta, a completely cored interval is present in the Anglo Home C & E. Elk Point No. 2 well (located in Lsd. 3, Sec. 14, Tw. 57, Rge. 6, west of the 4th meridian) between depths of 1083.2 and 1118.9 m (3554 and 3671 ft). According to Rice (1967, p. 45), the Salt member was partly cored in

two other wells, Imperial Crossroads (Lsd. 15, Sec. 32, Tw. 109, Rge. 19, west of the 5th meridian) between depths of 1436.5 and 1437.4 m (4713 and 4716 ft), and Imperial Surette Lake (Lsd. 15, Sec. 24, Tw. 109, Rge. 17, west of the 5th meridian) between depths of 1315.2 and 1321.3 m (4315 and 4335 ft). In the southern part of the District of Mackenzie, the Cold Lake salt was partly cored in the Imperial Davidson Creek P-2 well (Lat. 62°11'45.00"N, Long. 118°15'05.00"W) between depths of 656.5 and 663.2 m (2154 and 2176 ft). The Cold Lake salt in these cores is a reddish brown, semi-translucent, very coarsely crystalline (0.5-1 cm) halite (see Fig. 38d), which contains varying amounts of red brown shale. Interbeds of red-brown, dolomitic shale are also present.

Mirage Point Formation. Belyea and Norris (1962) used the name Mirage Point Formation for a variable sequence of redbeds lying between the Chinchaga Formation above and a basal Paleozoic sandstone below. Because only the upper part of the formation is exposed on the northwestern shore of Great Slave Lake, Norris (1965) included a description of the lithology of the Mirage Point in three subsurface sections. The section in the Northwest Windy Point No. 1 well (Lat. 61°19'00"N, Long. 115°52'00"W) may be used as a reference. The interval assigned to the Mirage Point Formation in this well was described earlier by Cameron (1922) under the name "Red Beds". It overlies a basal Paleozoic, red and reddish brown sandstone, and underlies a succession of dolomitic limestone, gypsum, and anhydrite (the Chinchaga Formation). Since the samples of the Windy Point No. 1 well were lost and borehole logs are not available, it is proposed (Meijer Drees, in press) to designate as the type section the interval between the depths of 437.4 and 598.9 m (1435 and 1965 ft) in the Horn River et al. Hay River B-52 well (Lat. 60°51'04"N, Long. 115°40'17"N). The correlation between the Windy Point No. 1 and the Hay River B-52 wells is shown in Figure 40.

In the Hay River well, the Mirage Point Formation transitionally overlies a reddish brown sandstone bed, which unconformably overlies Precambrian granitic rocks. Belyea and Norris (1962), Norris (1965), and Rice (1967) correlated this sandstone bed with the Cambrian Old Fort Island Formation and assumed that the overlying Mirage Point Formation was pre-Devonian. They postulated an unconformity at the top of the formation. Subsurface correlations in the Great Slave Plain, established by Law (1971), Williams (1974), and Meijer Drees (1975), suggest that the reddish brown sandstone bed belongs to the lower Elk Point subgroup and may represent a discontinuous, basal, transgressive deposit, similar to the La Loche Sandstone described by Norris (1963).

The Mirage Point Formation in the Hay River well can be subdivided into two parts. The lower part includes reddish brown, dolomitic shale, siltstone, and minor dolostone. The upper part is an interbedded succession of halite, anhydrite, and reddish brown shale. It includes two salt beds and it can be correlated with the Ernestina Lake, Cold Lake, and Contact Rapids formations of Alberta. The top of the Mirage Point Formation is selected at the highest occurrence of reddish brown, dolomitic shale, and coincides with the base of the Chinchaga Formation as defined by Law (1955).

The correlations on the structural cross-sections, A₁-A₂ and A₂-A₃ (figs. 26, 27) suggest that the Mirage Point Formation not only includes equivalents of the Contact Rapids, Cold Lake, and Ernestina formations, but also includes equivalents of the Lotsberg Formation. The formation is thus more or less equivalent to the "Basal Red Beds" unit of Sherwin (1962), without the basal Devonian

sandstone unit. It is thus possible to regard the formations introduced by Sherwin (1962) as members of the Mirage Point Formation. This procedure is followed in the subsurface of the southern District of Mackenzie, and the Cold Lake Salt is indicated as a member of the Mirage Point Formation in figures 40, and 43.

The structural cross-section in Figure 26 indicates that the Mirage Point Formation merges northwestward into the middle part of an interbedded unit of anhydrite and dolostone (the Bear Rock Formation), and that the reddish shale unit overlying the Cold Lake Salt Member disappears in the same direction. The top of the Mirage Point Formation in the subsurface of Horn Plateau is thus picked at the top of the highest occurrence of salt. This procedure is followed in the structural cross-section in Figure 30. The cross-section also shows the facies changes between the Mirage Point, the Bear Rock, and the Arnica formations.

Structural cross-section A₁-A₂ (Fig. 26) indicates that the thickness and distribution of the lower part of the Mirage Point Formation is influenced by pre-Devonian paleotopography. The paleotopographic depression in the Great Slave Lake region is separated from the paleotopographic depression in the Keller Lake region by a relatively high area, over which the lower part of the Mirage Point Formation is absent.

Northwest of this relatively high paleotopographic feature, the Mirage Point Formation consists of interbedded light brown or brown, microcrystalline dolostone, light grey anhydrite, and semi-translucent or reddish brown halite. A thin unit of reddish brown, very fine grained, sandy, dolomitic siltstone is locally present at the base of the formation, and the uppermost bed is a reddish brown and greenish grey mottled, anhydritic, and dolomitic shale.

The Mirage Point Formation includes several salt members, two of which are named. The other, unnamed salt members, are thin and have a local distribution. The lower part of the Mirage Point Formation, in the Northwest Windy Point No. 1 well, includes a salt bed about 3 m (10 ft) thick, which is represented in the Hay River well by a unit of dolostone with salt-plugged vugs and anhydrite (see Fig. 40). The upper part of the Mirage Point Formation in the same wells includes two salt members which have been mapped. The lower of the two members is mapped as a part of the Johnny Hoe member (Meijer Drees, in press) in Figure 43 and is about 6 m (20 ft) thick in the Windy Point No. 1 and Hay River B-52 wells.

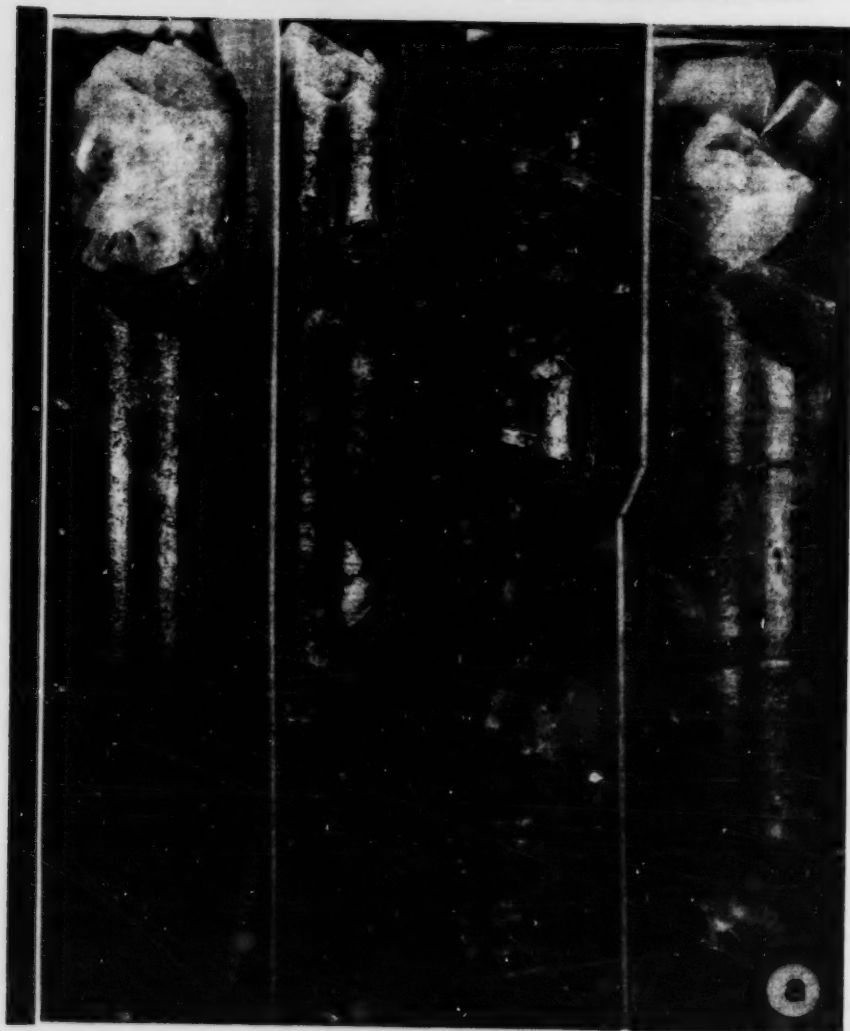
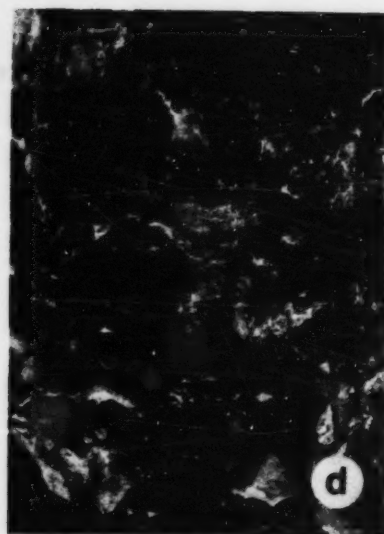
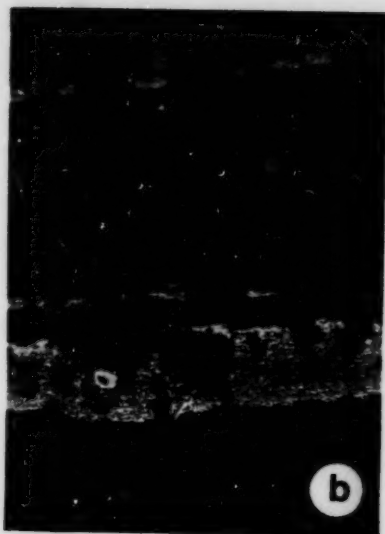
In the subsurface of Horn Plateau, the Johnny Hoe Salt varies in thickness between 0 and 21.6 m (71 ft) (see Fig. 44). It was cored in the IOE Trail River P-13 well (Lat. 62°02'59"N, Long. 121°32'13"W) and consists of semi-translucent, crystalline halite, with minor amounts of grey anhydrite.

In the Imperial Davidson Creek P-2 well (Lat. 62°11'45"N, Long. 118°15'05"W), the Johnny Hoe member is underlain by a local, unnamed salt bed, 7.9 m (26 ft) thick. The upper part of the unnamed salt bed was cored and consists of a laminated mixture of halite, anhydrite and dolostone (see figs. 38b, c, 45a).

The Cold Lake Member of the Mirage Point Formation is widely distributed in the southern part of the District of Mackenzie and was mapped in Figure 42. The member varies in thickness between 0 and 117 m (384 ft) and the upper part of the salt was cored in the Imperial Davidson Creek P-2 well. Here, it is a reddish brown semi-translucent, very coarse, crystalline halite, which includes much reddish brown dolomitic shale between the crystals (see Fig. 38d).

Figure 38. Photographs of core samples, Lower Elk Point evaporite, salt facies (true to scale, except a).

- a. Upper Lotsberg Salt, Chemcell Duvernay NACL well; 16-27-55-12W4; Alberta; unspecified depth intervals. Light grey, locally reddish brown halite and clear halite. Crystal size varies between 2 and 15 cm. In the dark beds, reddish brown dolomitic claystone occurs as partings between salt crystals. Breccia bed is a mixture of light grey dolostone and reddish brown shale fragments.
- b. Interbedded and crossbedded, halite-impregnated, anhydritic dolomite-mudstone. In the dark circular patches dolomite is replaced by halite. Mirage Point Formation; Imperial Davidson Creek P-2 well; Lat. 62°11'45"N, Long. 118°15'05"W; Mackenzie; depth 2540 feet (774.2 m).
- c. Greyish brown, dolomitic and anhydritic wackestone with scattered, subhedral halite crystals. Light coloured beds are mainly dolomite, dark coloured beds mainly anhydrite. Some beds are laminated mudstones, others contain many pale, deformed, fine to coarse mud clasts. Bedding is disrupted by fenestral voids filled with halite and by displacive halite crystals (arrows). The halite crystals contain very fine pyrite crystals. Mirage Point Formation; Imperial Davidson Creek P-2 well; depth 2528.5 feet (770.7 m).
- d. Yellowish brown halite with laminated inclusions of reddish brown, dolomitic shale (arrow). Inclusions are probably remnants of original host sediment (see fig. 15a). Cold Lake Salt; Imperial Davidson Creek P-2 well; depth 2161 feet (658.7 m).
- e. Conglomerate composed of greenish grey and reddish brown, dolomitic shale pebbles in matrix of reddish brown shale and clear and white mottled anhydrite. Anhydrite has filled voids, but also occurs as nodules. Part of anhydrite is transformed into clear, subhedral gypsum crystals. Shale pebbles are dark, gypsum is grey and anhydrite white. Upper Redbed member, Mirage Point Formation; Imperial Davidson Creek P-2 well; depth 2125 feet (647.7 m).
- f. Greyish brown, nodular, dolomitic anhydrite-mudstone, sharply overlain by interbedded, dark grey, argillaceous and greyish brown, non-argillaceous anhydrite-mudstone. Nodular mudstone contains irregular inclusions of halite and burrow-like structures filled with laminated sediment. Arrow points to cavity partly filled with sediment, partly filled with halite. Halite contains very fine pyrite crystals. The sharp contact above the nodular mudstone probably represents a hiatus. Above the contact beds are discontinuously laminated and contain light coloured, coarse to very coarse mud clasts. The bedding is disturbed by dark, irregularly shaped anhydrite nodules, similar to those seen in Figure 54g. Mirage Point Formation; IOE Trail River P-13 well; Lat. 62°02'59"N, Long. 121°32'13"W; District of Mackenzie; depth 2284 feet (696.2 m).



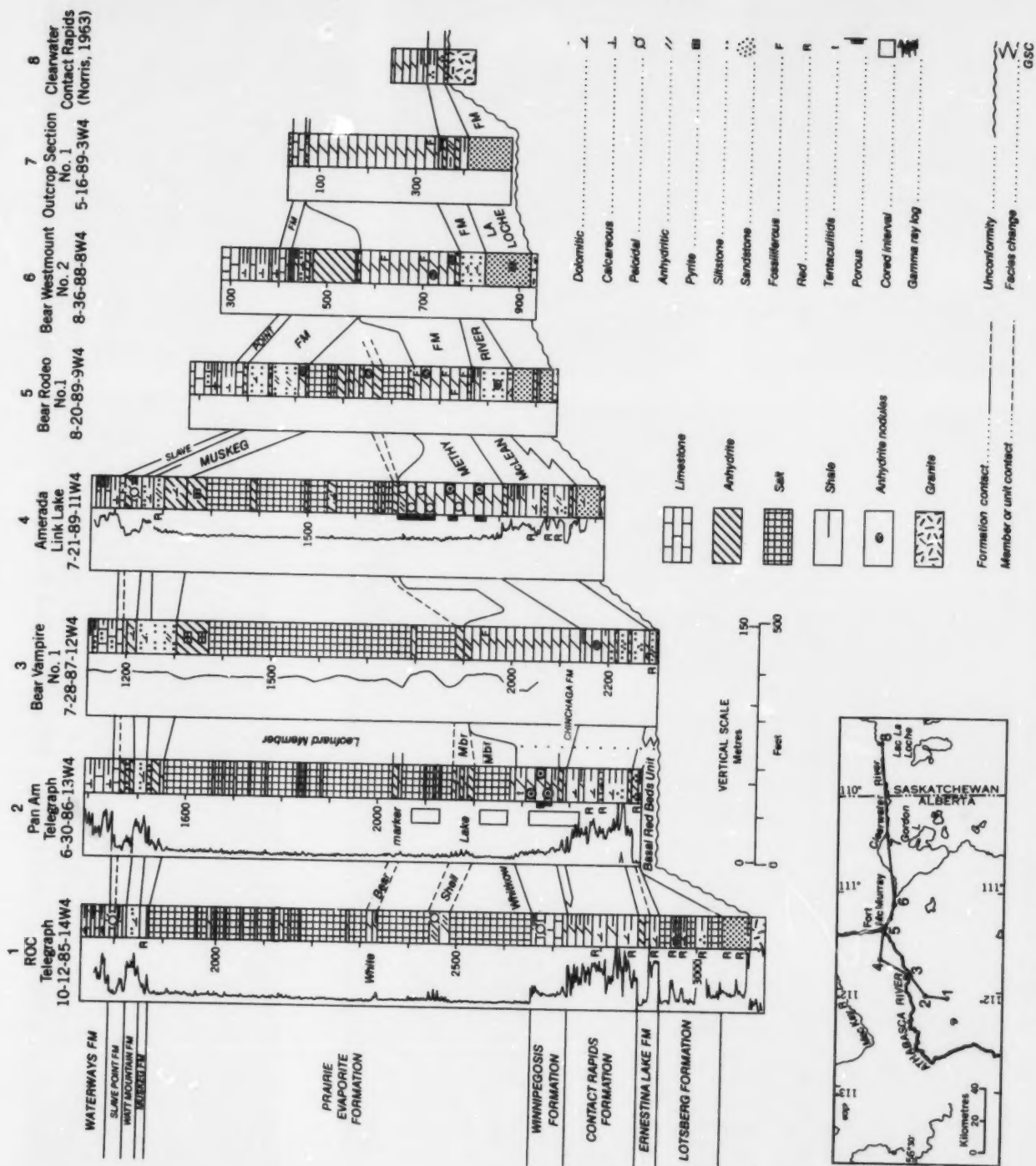


Figure 39. Stratigraphic cross-section, Elk Point Group, eastern Alberta and western Saskatchewan.

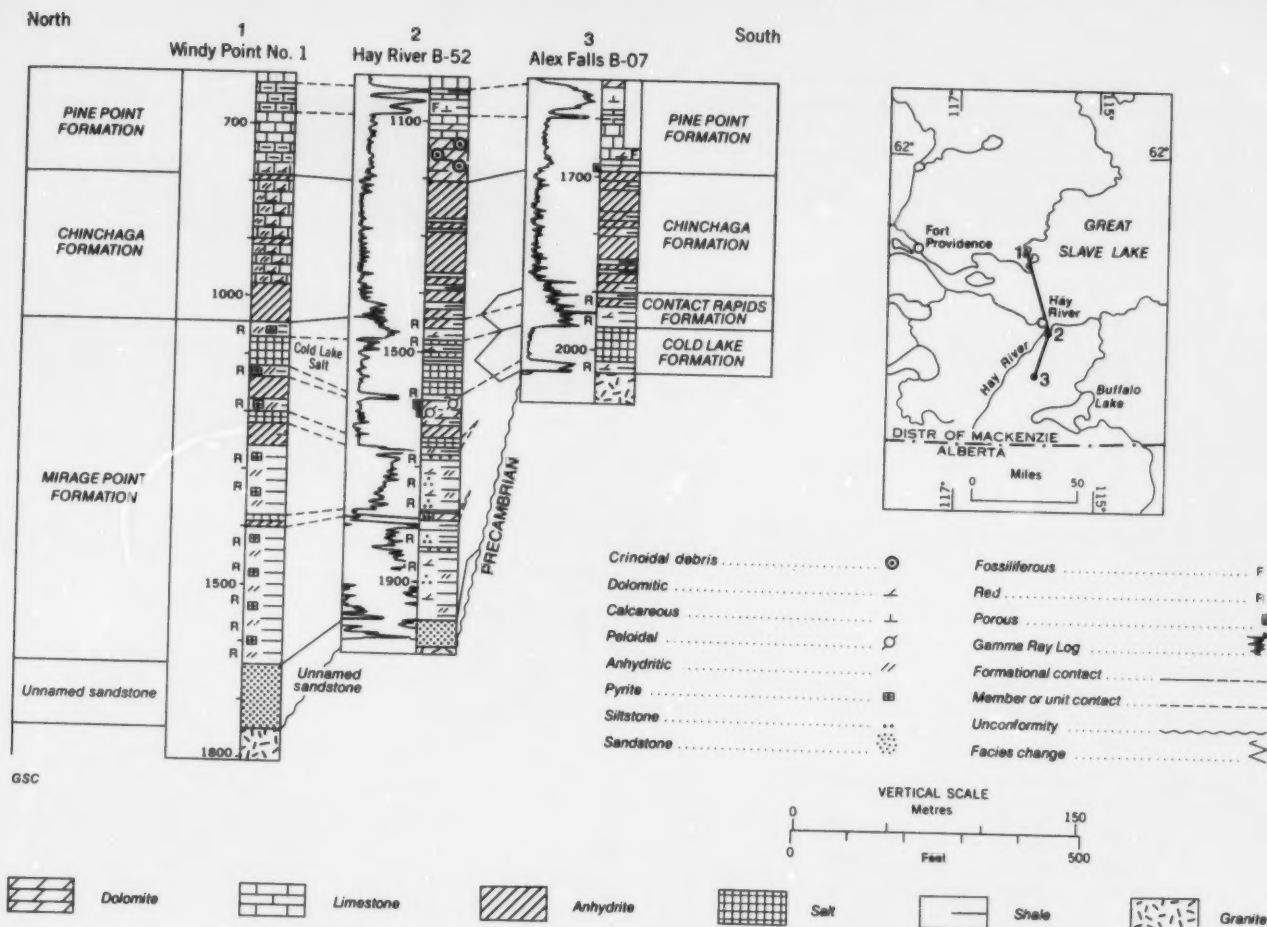


Figure 40. Stratigraphic cross-section, Lower Elk Point subgroup, Great Slave Lake region.

The southwestern limits of the Johnny Hoe and Cold Lake members in the District of Mackenzie are the result of depositional onlap against a paleotopographic high area, the Tathlina Uplift. The western and northwestern limits are facies changes from massive halite to interbedded halite and anhydrite, and from halite to anhydrite (see figs. 26, 30). The northeastern limits of both salt members are probably due to dissolution. Structural cross-section B₁-B₂ (Fig. 30) indicates that the beds overlying the Cold Lake salt north-west of the Imperial Willow Lake B-28 well have collapsed.

Bear Rock Formation. The name Bear Rock Formation was introduced by Hume and Link (1945) to describe the succession of nonbedded gypsiferous carbonates, gypsum, and carbonate breccia in the Fort Norman area of the Mackenzie District, "lying below Middle Devonian strata and above a sharp disconformity with well bedded Silurian limestones". The upper contact of the formation was defined at the base of a 3 m (10 ft) thick unit consisting of "bedded limestone and dolomite breccia" below the "Ramparts" Formation. At the type section, the Bear Rock Formation consists of massive or poorly bedded, calcareous or dolomitic breccia and is about 154 m (505.2 ft) thick (Morrow and Meijer Drees, 1981). The formation abruptly overlies the Cambro-Silurian Franklin Mountain Formation and is overlain by bedded, unfossiliferous limestone. It is probable that the bedded limestone belongs to the Landry Formation. In other places where the contact between brecciated limestone and bedded limestone is

difficult to define, the bedded, unfossiliferous limestone was mapped together with the Bear Rock Formation (Bassett, 1961).

In most surface exposures in the northern Franklin and eastern Mackenzie Mountains, the Bear Rock Formation is a chaotic, calcareous and dolomitic breccia containing angular to slightly rounded dolostone or limestone fragments. The Bear Rock Formation is, in general, poorly exposed and the upper and lower contacts are concealed or disturbed by brecciation.

The Bear Rock Formation was mapped in the southern Franklin and Mackenzie mountains by Douglas and Norris (1963) and was shown to be equivalent to the combined stratigraphic interval occupied by the Arnica, Landry and Manetoe formations. Aitken and Cook (1974) mapped the Bear Rock Formation in the Carcajou River area of the Mackenzie Mountains and discussed the relationship between the Bear Rock, the Camsell, and the Delorme formations.

In the Colville Hills area, the Bear Rock is exposed in many sinkholes. It consists of laminated to thick bedded, pale brown, very finely crystalline dolostone; thinly bedded, pale grey weathering, pelletal limestone, and rarely exposed, white gypsum (Cook and Aitken, 1971). Thick units of dolostone and limestone breccia are present and the bedded carbonates are commonly brecciated. In the subsurface, the stratigraphic equivalents of the Bear Rock Formation occur

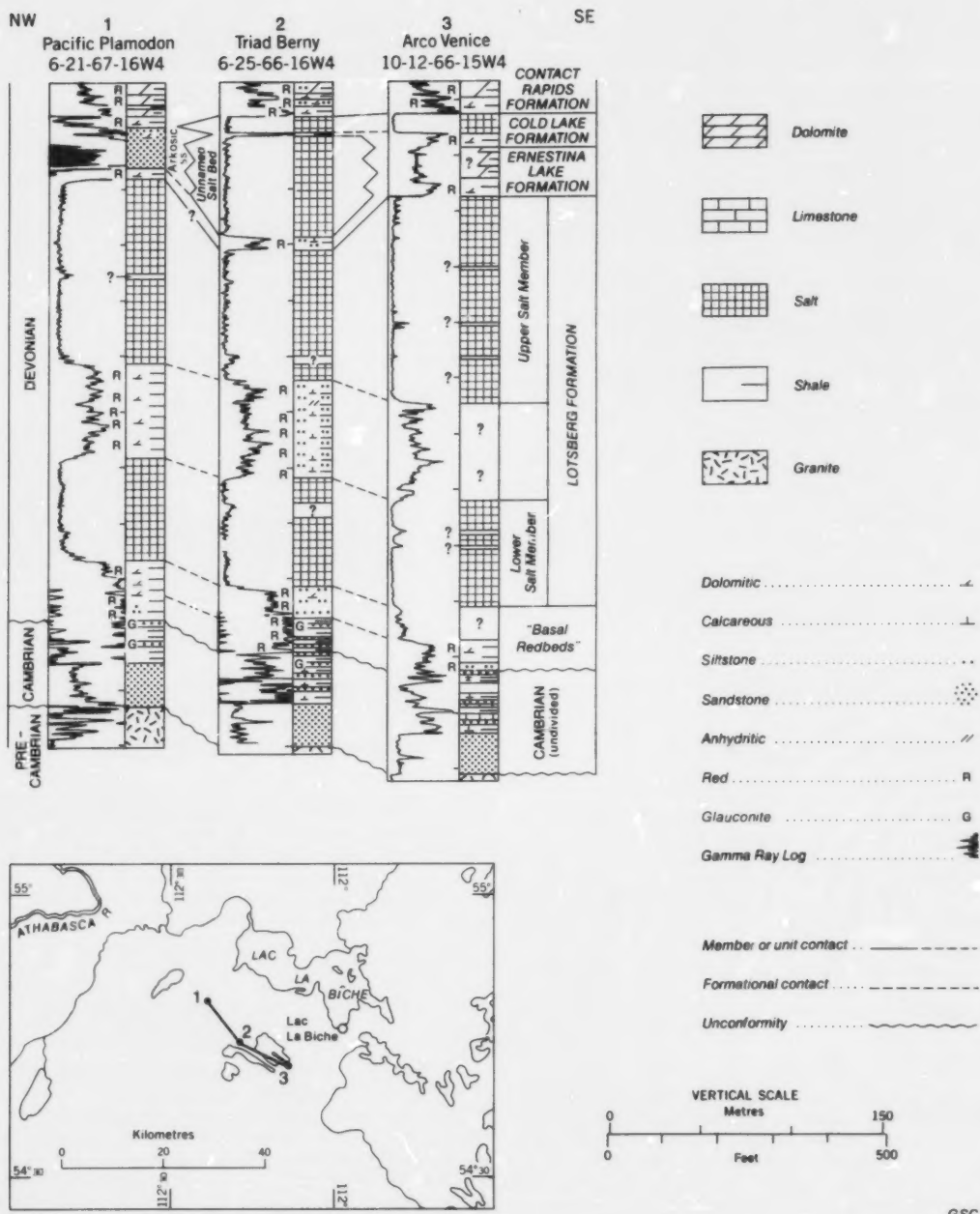


Figure 41. Lower Elk Point strata in the Berry well, central Alberta.

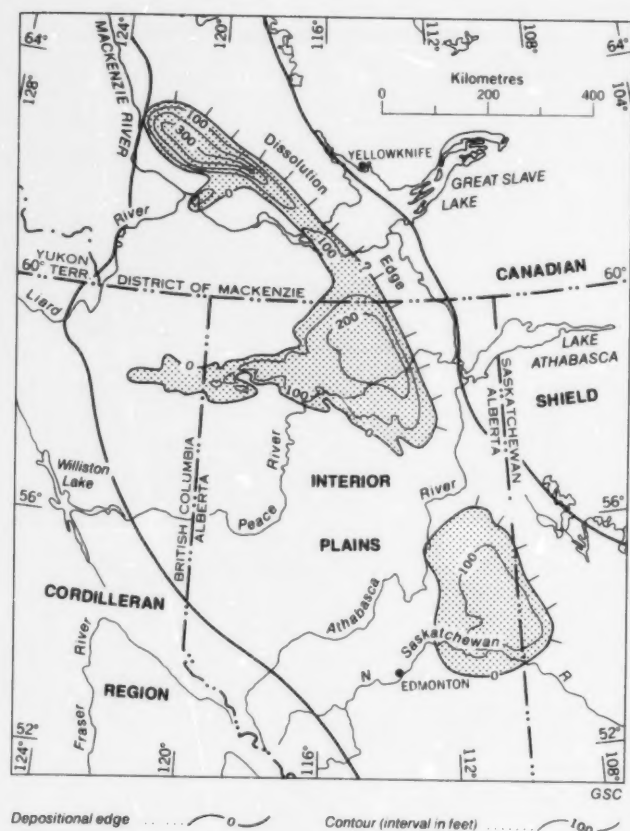


Figure 42. Isopach map, Cold Lake Salt, Alberta and District of Mackenzie.

in two facies. The first facies is an interbedded succession of light coloured, commonly laminated dolostone and anhydrite, which is brecciated and contains veins of white calcite, white anhydrite, and pale green, siliceous shale. The second facies is not brecciated and consists of an interbedded succession of light to dark grey, commonly laminated, micro- to finely-crystalline dolostone and light grey, micro- to very finely-crystalline, nodular or nodular-bedded anhydrite.

Stewart (1945) and Hume (1954) used the term Bear Rock Formation in the subsurface of the Fort Norman area. They defined the top of the formation in the subsurface at the highest occurrence of dolostone. The base of the formation was erroneously placed somewhere in the middle of the interbedded succession of anhydrite and dolostone. Tassonyi (1969) detected the error and correctly established the sub-Devonian unconformity in the Imperial Vermilion Ridge No. 1 well (Lat. $65^{\circ}07'51''N$, Long. $126^{\circ}05'00''W$) at the base of the evaporites. He selected the Vermilion Ridge No. 1 well as the reference section for the Bear Rock Formation in the subsurface and redefined the boundaries. The top of the formation lies below a unit of pelletal limestone which is locally dolomitic. In the Vermilion Ridge No. 1 well, the Bear Rock Formation, as defined by Tassonyi (1969), includes two members, an upper dolomitic member and a lower anhydritic member. The Upper member is in mappable continuity with the Arnica Formation, the Lower member is a facies equivalent of the Arnica Formation (Meijer Drees, 1980).

Williams (1975) noted the presence of a pre-Devonian paleotopographic depression in the area southeast and east of Fort Norman, and recent work in the same area by Meijer Drees (in press) suggests that, in this paleotopographic depression, the light and dark layered succession of the Bear Rock Formation overlies a light coloured succession of dolostone, silty dolostone, anhydrite, and minor, reddish brown, silty shale, which is approximately equivalent to the lower part of the Camsell Formation.

Because the Bear Rock Formation includes the interval between Middle Devonian and Silurian strata, one may argue that the Camsell equivalents in the subsurface of the southern Great Bear Plains are part of the Bear Rock. The nomenclature used at present is under review, and new formational names have been proposed for the Evaporitic member of the Bear Rock Formation and the subsurface equivalents of the Camsell Formation (Meijer Drees, in press).

The Evaporitic member of the Bear Rock Formation (see Tassonyi, 1969) is widely distributed in the northern Interior Plains and the Mackenzie Mountains (see Fig. 46). It reaches a thickness of about 487.6 m (1600 ft) in the subsurface east of the McConnell Range and south of Blackwater Lake. The eastern limit of the Evaporitic member of the Bear Rock Formation coincides with the facies change to interbedded halite, anhydrite and dolostone (the Mirage Point Formation). This facies change is shown on structural cross-sections A₁-A₂ (Fig. 26) and B₁-B₂ (figs. 30, 43). The western limit of the Evaporitic member coincides with the facies change from anhydrite to dolostone. This boundary is shown in Figure 30 as the facies change between the Arnica and Bear Rock formations. On the structural cross-section of Figure 21, the Evaporitic member of the Bear Rock Formation changes northeastward into interbedded limestone and dolostone. The lithology of the Evaporitic member of the Bear Rock Formation, in the area just northwest of the facies change to the Mirage Point Formation, is dominated by greenish grey and dark grey, bedded, or nodular-bedded anhydrite, and light brown, laminated, anhydritic dolostone (see Fig. 46). The anhydrite is somewhat argillaceous and nodular-bedded, and indistinctly laminated or crosslaminated. Indistinctly bedded or massive sedimentary breccias, are also present (see Fig. 45b). The dolomitic interbeds are very finely peloidal, and contain mudclasts, "calcspheres", cryptalgal laminites, and white, deformed anhydrite nodules (see Fig. 45c, d, f).

Near the facies change to the Arnica Formation, the Evaporitic member is commonly interbedded with grey and dark grey, indistinctly laminated dolostone, containing "calcspheres", or rarely *Amphipora* sp., gastropods and crinoid ossicles. The anhydrite is dolomitic and nodular-bedded, laminated or crosslaminated. The cores in the Candex et al. Dahadinni M-43A well (Lat. $63^{\circ}62'59.3''N$, Long. $124^{\circ}39'15.1''W$) were described by Meijer Drees (1980) and, at this location, the dark grey dolostone, the light grey nodular-bedded anhydrite, and the laminated anhydrite form regressive sedimentary sequences or "upward shoaling cycles" (see Fig. 45e).

Contact Rapids Formation. Sherwin (1962) proposed the term Contact Rapids Formation in east-central Alberta for a succession of dolostone and dolomitic shale that overlies the Cold Lake Salt and underlies the Winnipegosis Formation. The type section is between depths of 937.4 and 982.0 m (3076 and 3222 ft) in the Anglo Canadian Seaboard Ernestina Lake well (Lsd. 10, Sec. 13, Tw. 60, Rge. 4, west of the 4th meridian). Here, it consists of a lower member, 9.7 m (32 ft) thick, of greenish grey and red, argillaceous dolostone and

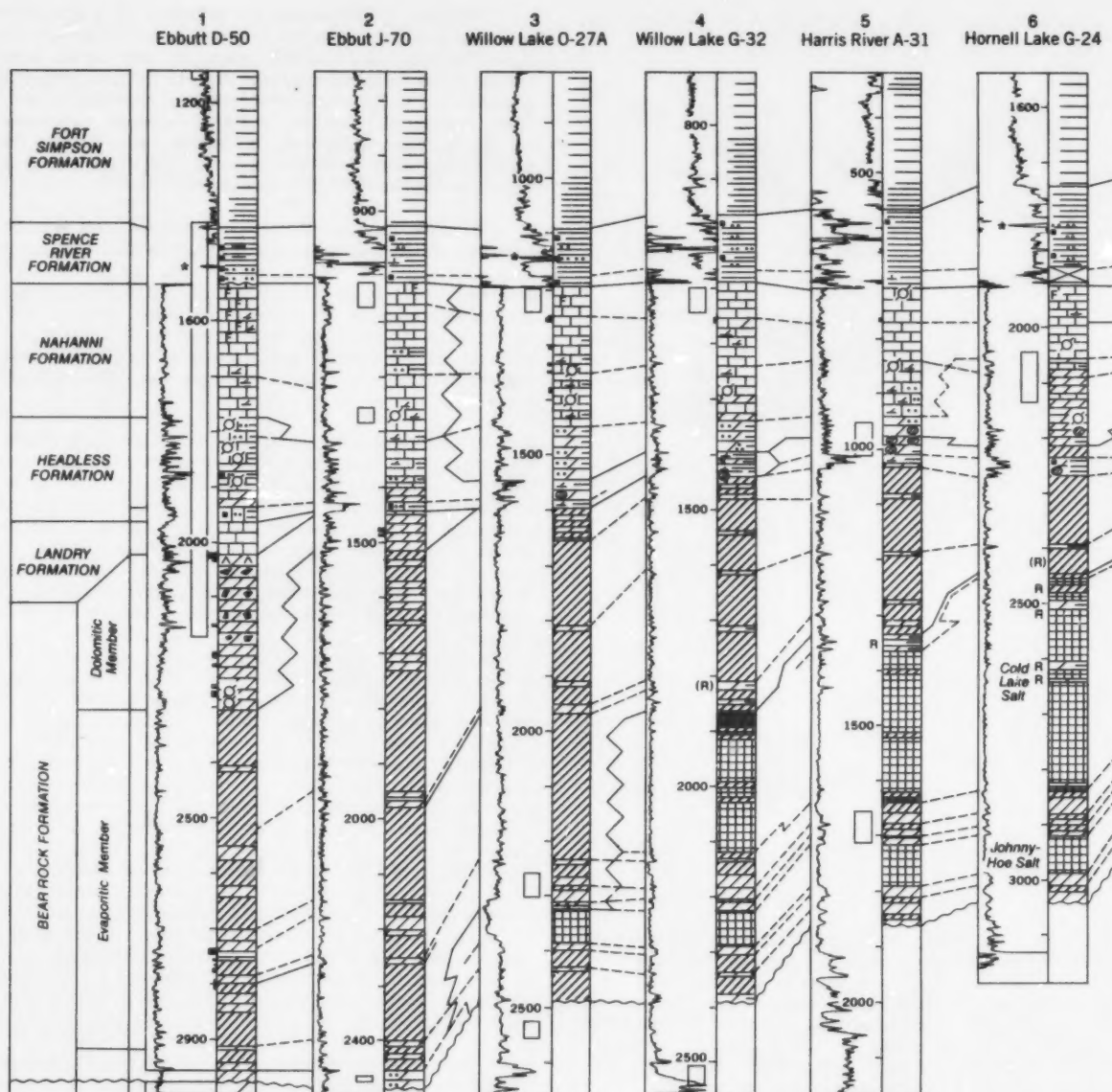


Figure 43. Stratigraphic cross-section, Lower Elk Point Subgroup, southern District of Mackenzie.

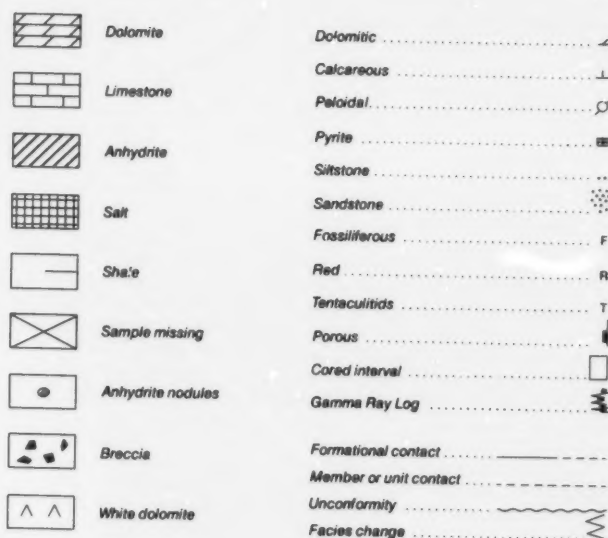
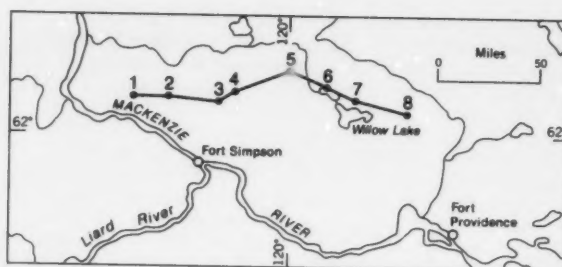
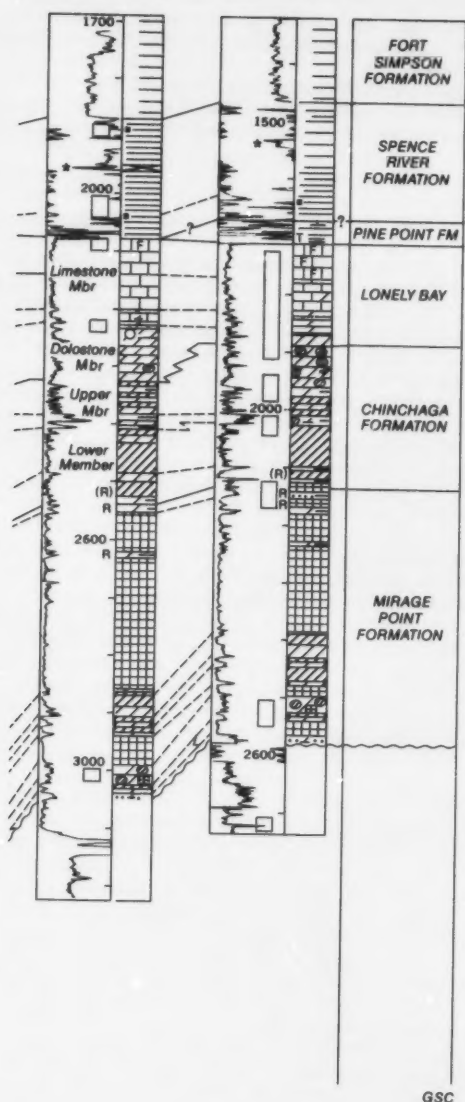
red dolomitic shale; and an upper member, 34.7 m (114 ft) thick, of brownish grey, very argillaceous dolostone and dolomitic shale.

Equivalents of the Contact Rapids Formation are exposed along the Clearwater River in Saskatchewan and were described by Norris (1963) under the name McLean River Formation. In this section, the McLean River Formation overlies the LaLoche Formation and underlies fossiliferous dolostone of the Methy Formation. It consists of interbedded, light brown, sandy and calcareous dolostone, greenish grey, silty, and sandy shale, and green shale. The unit contains tentaculitids and brachiopod moulds. The McLean River Formation is only 18.5 m (61 ft) thick, and the underlying LaLoche sandstone, which overlies Precambrian granitic rocks, is 1.5 m (5 ft) thick. Correlations with

subsurface sections to the west suggest that the Lower Elk Point rocks in this region onlap a pre-Devonian paleotopographic high area (see Fig. 39), and become increasingly sandy at the base. The McLean River Formation is thus equivalent to the upper part of the Contact Rapids Formation farther west.

The Contact Rapids Formation and its equivalents are widely distributed in central Alberta, as was shown by Sherwin (1962) and Grayston et al. (1964). They fringe the northern edge of the Peace River Arch and extend into the subsurface of northeastern British Columbia (see Grayston et al., 1964, figs. 5-11b). In the area where the Cold Lake Salt is absent, near Pre-Devonian paleotopographic high areas such as the Peace River Arch, Sherwin (1962) and Grayston et al. (1964, figs. 5-10) have used the top of the

7 Willow Lake B-28 Davidson Creek P-2



Ernestina Lake Formation to define the base of the Contact Rapids Formation. The sandy equivalents of the Contact Rapids Formation, which flank the southern part of the Peace River Arch, and directly overlie Cambrian or Precambrian rocks (the Grizzly sandstone of Grayston et al., 1964, Fig. 5-10; and the Assineau sandstone on structural cross-section D₁-D₂, Fig. 32), are equivalents of the Contact Rapids Formation. The LaLoche sandstone of the Clearwater River area may be regarded as being equivalent to the lower part of the Contact Rapids Formation (see Fig. 39).

The reddish coloured Lower member of the Contact Rapids Formation can be traced in northern Alberta wherever the underlying Cold Lake Salt is present. It forms the upper unit of the Mirage Point Formation in the southern District of Mackenzie (see structural cross-sections in figs. 26, 27).

The greenish grey Upper member of the Contact Rapids Formation grades northward into the interbedded succession of anhydrite and dolostone of the Chinchaga Formation (see Fig. 27). South of the Meadow Lake Escarpment (Fig. 28), the Contact Rapids Formation grades into the Ashern Formation. In the Ernestina Lake well, where the Contact Rapids Formation does not have an evaporitic character, only the lower reddish coloured beds may be regarded as evaporitic. However, in places where the formation includes the equivalents of the Cold Lake Formation, the shaly beds include interbeds or inclusions of anhydrite and gypsum. In several wells in east-central Alberta, there is a 1.5 to 3 m (5-10 ft) thick interval between the Winnipegosis and the Contact Rapids Formation which includes anhydrite or interbedded anhydrite and dolostone (see Fig. 39). These beds may be regarded as a feather edge of the Chinchaga Formation.



Figure 44. Distribution of Johnny Hoe Salt and equivalents, District of Mackenzie.

No published isopach or structural contour maps of the Contact Rapids Formation are available. In the subsurface, the formation onlaps the crestal part of the Peace River Arch and a depositional zero edge was mapped by Grayston et al. (1964, figs. 5-11b). The maximum thickness of about 76.2 m (250 ft) occurs in the area southeast of Lesser Slave Lake where the Cold Lake Salt is absent (see Fig. 32).

Chinchaga Formation. This formation was proposed by Law (1955) for a pale, interbedded succession of anhydrite and dolostone in the subsurface of northern Alberta. The type section is located between depths of 1668.7 and 1731.2 m (5475 and 5680 ft) in the California Standard Steen River well, located in Lsd. 2, Sec. 22, Tw. 117, Rge. 5, west of the 6th meridian. The Chinchaga Formation overlies reddish brown, anhydritic, dolomitic, and argillaceous beds (the "red-beds of doubtful age"), which are equivalent to the Mirage Point Formation. The formation is overlain by yellowish brown dolostone of the Keg River Formation. Belyea and Norris (1962) mapped the Chinchaga Formation in the subsurface of the southern District of Mackenzie. Norris (1965) used the name for the unit of interbedded dolomitic limestone, dolostone, gypsum, and anhydrite in the Great Slave Lake region, which was previously mapped as the Fitzgerald Formation (Cameron, 1922; Law, 1955; Campbell, 1957). The Chinchaga Formation is a recessive unit and is poorly exposed in northeastern Alberta, and the southeastern part of the District of Mackenzie, west of Slave River and northwest of Slave Lake (Norris, 1962, 1965).

In the subsurface, the formation is widely distributed in northern Alberta, northeastern British Columbia, and in the southern part of the District of Mackenzie (see Fig. 43). It overlies redbeds of the Contact Rapids Formation in areas where the Cold Lake Salt is present. In areas where the Cold Lake Salt is absent, the Chinchaga Formation overlies the "Basal Red Beds" unit. The lower contact is defined at the "highest sign of reddish coloration at the top of the redbeds" (Law, 1955, p. 163).

The southern limit of the Chinchaga Formation is a facies change. The succession of interbedded anhydrite and dolostone of the Chinchaga Formation grades southward into the upper part of the Contact Rapids Formation, a succession of interbedded argillaceous dolostone and shale. The facies change was mapped by Sherwin (1962) and Grayston et al. (1964) as an east-west trending line north of Peace River Arch. It parallels the ancient shoreline. The facies change is shown on the structural cross-section in Figure 27.

In northern Alberta, the Chinchaga Formation onlaps a pre-Devonian paleotopographic high area located in the southern part of the District of Mackenzie. Belyea (1971) described the geology of this paleotopographic feature and used the name Tathlina Uplift. She noted the presence of a sandy unit in the middle of the Chinchaga Formation, which forms a distinct marker on borehole logs south and southwest of it (Belyea, 1970). This marker also occurs in the Chinchaga Formation north of Tathlina Uplift, but here the lithology is a greenish grey, dolomitic and anhydritic shale. One can use the sandy and shaly beds to subdivide the Chinchaga Formation into three units, a lower anhydritic unit, a detrital marker, and an upper anhydritic unit. Belyea (1971) arbitrarily mapped the Lower anhydritic unit together with the underlying red shale of the Contact Rapids Formation in northern Alberta, as the Lower member of the Chinchaga Formation. Law (1971) introduced a new map unit in the southern District of Mackenzie (the Willow Lake Formation) for the interval including the detrital marker, the upper anhydritic unit, and a unit of dolostone that is a basal member of the Lonely Bay Formation. The writer rejects the Willow Lake Formation as a map unit, because the type section is poorly chosen and the use of the map unit unnecessarily complicates the nomenclature (Meijer Drees, in press). However, Law's proposal to name the detrital marker, Ebbutt Member, is useful.

The lower anhydritic unit of the Chinchaga Formation in northern Alberta consists of interbedded, light grey, crypto- to micro-crystalline, dolomitic anhydrite and grey, anhydritic dolostone. Sandy dolostone and green shale laminae are present in the basal part of the unit (Belyea, 1971; Law, 1955). The unit overlies reddish brown mottled shale, a tongue of the Contact Rapids Formation (see figs. 27, 29). In the southern part of the District of Mackenzie, the lower unit either overlies equivalents of the Contact Rapids Formation or one of the salt members of the Mirage Point Formation, and grades into the upper part of the Evaporitic member of the Bear Rock Formation (see figs. 26, 30). In northeastern British Columbia, the lower evaporitic unit of the Chinchaga Formation grades westward into subsurface equivalents of the Stone Formation (Taylor and Mackenzie, 1970; Griffin, 1967). This facies change is shown in Figure 31.

The detrital marker (or Ebbutt Member) of the Chinchaga Formation partly overlaps the Tathlina Uplift and consists of greenish grey, sandy, argillaceous and anhydritic dolostone, interbedded with dolomitic shale. In places, the Ebbutt Member overlies or grades into the basal Devonian sandstone beds that unconformably overlie Precambrian granite. The Ebbutt Member grades westward into the basal part of the Headless Formation (see figs. 26, 30). In the subsurface of Horn Plateau (see Fig. 40), the member was cored in several wells and includes, at the base, massive, unsorted, conglomerate beds composed of subangular pieces of laminated dolostone and greenish grey, silty shale. A local unconformity was postulated at the base of the member (see Belyea, 1971; Law, 1971). The upper anhydritic unit of the Chinchaga Formation overlaps most of the Tathlina Uplift and, in places, directly overlies the basal Devonian sandstone unit or Precambrian granite. The unit consists of

interbedded, light brown, micro- to crypto-crystalline dolostone and light grey anhydrite. The anhydrite occurs as nodular interbeds or as nodules, the dolostone is in places peloidal and laminated and contains *Charophyta oogonia*, "calcspheres", and stromatolitic structures.

In northeastern British Columbia and the southern part of the District of Mackenzie, the upper anhydritic unit grades into a unit of light brown, in places peloidal, dolostone, which includes flat-pebble conglomerates and incompletely dolomitized, fossiliferous limestone interbeds (see Fig. 45g). These beds grade westward into limestone of the upper part of the Headless Formation (see figs. 26, 30).

The Chinchaga Formation varies in thickness between 0 and 97.5 m (320 ft). No published isopach maps of the Chinchaga Formation are currently available, and the basal red shale unit of the Contact Rapids Formation and the lower anhydritic unit of the Chinchaga Formation were mapped together by Belyea (1971, Fig. 8). This interval varies between 0 and 60.9 m (200 ft). The upper anhydritic unit and the Ebbutt Member were mapped together as the Upper member of the Chinchaga Formation (Belyea, 1971, Fig. 9). In northern Alberta, this interval varies in thickness between 0 and 60.9 m (200 ft).

Stone Formation. The approximate equivalents of the lower unit of the Chinchaga Formation are exposed in the Front Ranges of the Rocky Mountains of northeastern British Columbia. These strata were mapped by Taylor and Mackenzie (1970) as the Stone Formation. This formation unconformably overlies a succession of sandstone, dolomitic sandstone, and argillaceous dolostone of Early Devonian age (the Wokkash Formation), and is overlain by a uniform succession of bedded, dark grey, argillaceous, and dolomitic limestone, known as the Dunedin or Pine Point Formation (see Macqueen and Taylor, 1974).

The formation is about 140.2 m (460 ft) thick in the Sikanni Chief River area of northeastern British Columbia and increases to about 591.3 m (1940 ft) just south of the boundary between British Columbia and Yukon Territory. It consists of light grey dolostone and dolostone breccia, and includes three facies. South of latitude 58°, the lower part of the Stone Formation includes much sandy dolostone and quartzose sandstone. Between latitudes 56°00'N and 58°30'N, the upper part of the Stone Formation is characterized by interbeds of dolostone breccia. North of latitude 58°30'N, the formation displays light and medium grey banding and contains only small amounts of quartz sand or breccia interbeds (Taylor and Mackenzie, 1970, p. 11).

The dolostone breccias in the upper part of the Stone Formation were described in more detail by Macqueen and Taylor (1974) and by Morrow (1975). They noted that the breccias are associated with white, very coarse, crystalline dolomite. The white dolomite is also seen in the great Slave Lake region and was mapped as the Presqu'île Formation (Norris, 1965). A similar dolomite facies is present in the southern Mackenzie Mountains and was mapped as the Manetoe Formation (Douglas and Norris, 1961, 1963). The white, brecciated dolomite facies contains minerals such as barite, sphalerite and galena. White dolomite is present as veins or as matrix in brecciated dolostone or limestone, in places filling vertical, karst-like caverns.

Information from the few wells drilled near the outcrop area of the Stone Formation indicates that subsurface equivalents of the Stone Formation consist of interbedded anhydrite and dolostone. The anhydrite beds are not exposed and may have been dissolved in the shallow subsurface by circulating groundwater.

Morrow (1974) suggested that the brecciation in the Stone Formation is due to dissolution of the anhydrite in the subsurface. The subsequent deposition of white dolomite in the brecciated parts of the Stone Formation may be due to the interaction between meteoric water and marine formation water. Meteoric water may have moved through the formation at periods of emergence. Each such period is recorded elsewhere as a hiatus in the rock succession. The earliest period during which fresh groundwater may have entered the subsurface is during the break in sedimentation associated with the hiatus at the base of the Watt Mountain Formation. It is almost certain that fresh water entered the Devonian succession during post-Mississippian, epeirogenic events.

If the brecciated facies of the Stone Formation at one time did include evaporites, this facies may correspond to the lower evaporitic unit of the Chinchaga Formation. It then becomes possible to correlate the facies change of the Stone Formation with the facies contact between the Contact Rapids and Chinchaga formations in the subsurface north of the Peace River Arch (see Fig. 31). The sandy facies of the Stone Formation represents the Contact Rapids Formation, and the brecciated facies corresponds to the Chinchaga Formation or the Evaporitic member of the Bear Rock Formation. The banded dolostone facies is equivalent to the Arnica Formation of the southern Mackenzie Mountains.

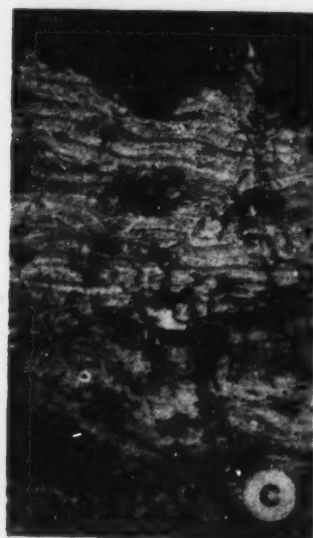
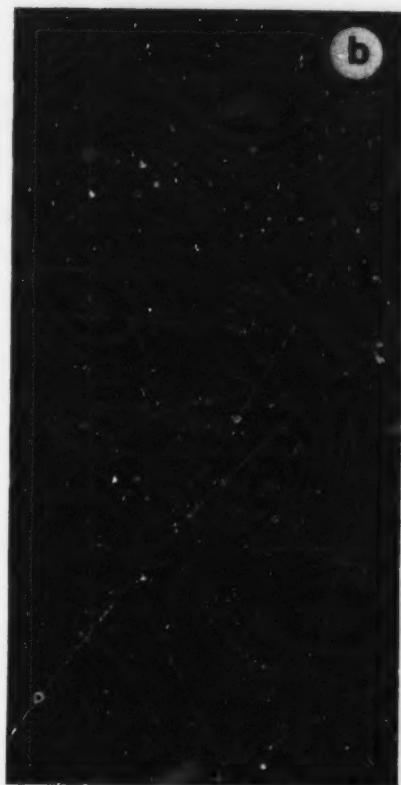
Cedared and Burnais formations. Rocks of early Middle Devonian age, including evaporites, are locally present in the southeastern part of the Cordilleran Orogen. They erosionally overlie rocks of Silurian age and are overlain by carbonates containing Middle Devonian (Eifelian) fossils (Norford, 1981). The evaporites were described by Henderson (1954) and named the Burnais Formation. They pass laterally into sandy dolostones (the Cedared Formation) which are similar to the "basal Devonian clastics" (Aitken, 1963), and are discontinuously present between the sub-Devonian unconformity and Upper Devonian carbonates. The Cedared and Burnais formations are missing in the subsurface of the southwestern Alberta Plains, because this area was emergent during the Middle Devonian (see figs. 25, 48).

The Cedared Formation is present in the Rocky Mountains of southeastern British Columbia in the Beaverfoot, Brisco, and Stanford ranges. The formation is about 213 m (700 ft) thick at the type section and consists of grey and yellowish brown dolostone, sandy and argillaceous dolostone, limestone, argillaceous limestone, mudstone, and breccia (Belyea and Norford, 1967). The Cedared Formation interfingers or passes laterally into the Burnais Formation. The Burnais is poorly exposed in the mountains but is well exposed in the three quarries at Windermere Creek. It consists of light and dark banded, laminated gypsum, with interbeds of grey, silty, or sandy limestone. The Cedared is conformably overlain by the Harrogate Formation, which contains fossils similar to those found in the Methy and Winnipegosis formations of the Upper Elk Point subgroup (Belyea and Norford, *op. cit.*).

Middle Devonian rocks are missing to the east in most of the southwestern Alberta Plains, and this region was probably emergent during Middle Devonian time (see figs. 25, 48). Both the Cedared and Harrogate formations pass eastward into the Mount Forester Formation (Norford, 1981), which includes silty and sandy dolostone, dolomitic sandstone, and much calcareous or dolomitic shale. The Mount Forester Formation is poorly fossiliferous but includes the fossil remains of fish and charophytes.

Figure 45. Photographs of core samples, Lower Elk Point evaporites, anhydrite facies (true to scale).

- a. Interbedded, light brown, dolomitic and greyish brown, anhydritic mudstones. Irregular edge on the right side of the photograph is edge of core. Beds cemented with halite have been partly leached. Dolomitic beds are very finely crystalline and cemented by halite or anhydrite. The uppermost beds contain fine to medium anhydrite nodules. Discontinuous, vertical fractures and small wedge-like voids are filled with halite. In the lower part of the sample, the bedding is distorted by irregular, light coloured, anhydrite nodules. Mirage Point Formation; Imperial Davidson Creek P-2 well; Lat. 62°11'45"N, Long. 118°15'05"W; District of Mackenzie; depth 2531 feet (771.5 m).
- b. Interbedded, light greyish brown, crosslaminated mudstone and conglomeratic floatstone. Mudstone is a microcrystalline, anhydritic dolostone locally containing very fine peloids and scattered, subangular mud pebbles. The conglomeratic beds include unsorted, laminated fragments of anhydrite-mudstone (dark) and dolomite-mudstone (light). Evaporitic member, Bear Rock Formation; IOE Strong Point G-24 well; Lat. 61°53'16"N, Long. 120°49'36"W; District of Mackenzie; depth 2112.5 feet (643.9 m).
- c. Light brown, stromatolitic dolostone containing dark greyish brown patches and crystal aggregates of anhydrite. In the upper part of the sample the stromatolite is completely anhydritized. Dolomitic member; Bear Rock Formation; Fina et al. Willow Lake L-59 well; Lat. 62°98'40"N, Long. 121°56'00"W; District of Mackenzie; depth 1349 feet (411.2 m).
- d. Thin section of sedimentary structures in laminated mudstone. Dark grey layers are dolomitic, light grey beds are anhydritic. Thick bed at top of sample grades upward into nodular anhydrite. Coarser beds are graded and some beds are bounded by scoured surfaces. One bed is inclined, laminated and contains scattered peloidal grains in a dolomite matrix, partly replaced by subhedral, anhydrite crystals. Evaporitic member; Bear Rock Formation; IOE Strong Point G-24 well; Lat. 61°53'16"N, Long. 120°49'36"W; District of Mackenzie; depth 2096 feet (638.9 m).
- e. Upper part of a regressive sedimentary sequence. Light coloured bed at base is a parallel laminated, microcrystalline, somewhat dolomitic anhydrite-mudstone. Basal unit is overlain by a thin interval with curled up bed fragments. This desiccated layer was deposited in a supratidal environment. It is sharply overlain by an unsorted wackestone composed of light coloured, dolomitic mud clasts, grey anhydrite nodules and a matrix of microcrystalline, anhydritic dolomite. This wackestone is sharply overlain by a dark grey, microcrystalline, anhydrite-mudstone. Sharp contact marks presence of a depositional hiatus. Evaporitic member; Bear Rock Formation; Candex et al. Dahadinni M-43A well; Lat. 63°52'59.3"N, Long. 124°39'15.1"W; District of Mackenzie; depth 5588.5 feet (1703.4 m).
- f. Brown, anhydritic dolomite-mudstone partly disrupted by elongate, greyish brown anhydrite nodules. Nodules are dark, cryptocrystalline, and have a distinct white gypsiferous edge. Arrow points to a scoured surface overlain by a laminated layer which is broken into angular fragments. Upper part of sample is wavy laminated and composed of micronodular layers of dolomite and darker layers of silty dolostone. It contains scattered, light coloured, medium to coarse, subhedral anhydrite crystals. Sample is cut by a veinlet of gypsum. Evaporitic member; Bear Rock Formation; Imperial Cartridge B-72 well; Lat. 63°11'19"N, Long. 120°29'04"W; District of Mackenzie; depth 1301 feet (396.6 m).
- g. Sample includes three beds. Basal bed is greyish brown, nodular anhydrite and includes discontinuous, subhorizontal veins of gypsum. Nodular bed is overlain by a light brown dolomite-mudstone with greenish grey, discontinuous, shale laminae. This grades upward into a greyish brown dolostone containing dark aggregates of subhedral anhydrite crystals, scattered microcrystalline pyrite, relicts of calcite cement and anhydrite-filled fenestral vugs. The bedding of the mudstone is distorted by scouring or desiccation. It is overlain by a flat-pebble conglomerate. This conglomerate bed forms the upper part of the sample. It is composed of light coloured dolomite-mudstone fragments and a dark anhydritic matrix. Scattered, dark, subhedral and euhedral anhydrite crystals are present. The succession shown in this sample is typical of an evaporitic, supratidal environment. Chinchaga Formation; Chevron Harris River A-31 well; Lat. 62°30'02"N, Long. 120°06'00"W; District of Mackenzie; depth 983 feet (299.6 m).



Ashern Formation. The Ashern Formation was defined by Baillie (1950) as a map unit in the outcrop area of the Paleozoic succession in southwestern Manitoba. It is a unit of brick red to greyish orange, argillaceous dolostone, which overlies beds of Silurian age with erosional unconformity and is unconformably overlain by the Elm Point limestone. The thickness of the formation could not be measured in outcrop sections. However, in the nearby subsurface, the thickness varies from a few centimetres to 4.5 m (25 ft). McCabe (1967) reported a maximum thickness of 12.1 m (40 ft) in wells at the south end of Lake Manitoba. The age of the Ashern Formation in the outcrop area is unknown because the redbeds are unfossiliferous. The overlying Elm Point limestone contains Devonian fossils of the Eifelian Stage (Norris and Uyeno, 1971; Norris et al., 1982).

Baillie (1953) correlated the red and green beds at the base of the Devonian succession in the subsurface of Manitoba and Saskatchewan with the Ashern Formation. In the subsurface, the basal redbeds are between 3 and 15.2 m (10 and 50 ft) thick and consist of reddish brown, sandy shale, overlain by green or reddish brown and green mottled dolomitic shale, and greenish grey, nodular, argillaceous, in places fossiliferous, dolostone. The redbeds unconformably overlie Silurian or Ordovician carbonates and are transitionally overlain by the Winnipegosis Formation (see Fig. 34). The shale beds form a good marker on the gamma ray log, and the upper contact of the Ashern Formation in the subsurface is thus defined by the disappearance of argillaceous interbeds, rather than by the change in colour from red to green. Walker (1957) divided the Ashern of southwestern Saskatchewan into a lower reddish and an upper grey member and mapped the complementary thickness variations of the two members. Jones (1965) observed a similar situation in west-central and southern Saskatchewan. Northwest of the Meadow Lake Escarpment the Ashern Formation grades into the upper part of the Contact Rapids Formation (see Fig. 28). The Ashern Formation does not include gypsum, anhydrite, or salt and it is thus not an evaporitic redbed. The reddish colour is probably derived from weathering products of the underlying Ordovician and Silurian carbonates. In places, the lower part of the Ashern contains dolostone pebbles derived from the underlying Silurian Interlake Group (Norris et al., 1982).

"Meadow Lake Beds". In the subsurface southwest of the Devonian outcrop area, near the margin of the Canadian Shield, the Lotsberg and Cold Lake salt beds are absent and the Lower Elk Point subgroup cannot be subdivided in the same way as in the area where the salt beds are present. Structural cross-section E₁-E₂ (Fig. 33) demonstrates that the beds overlying the lower Elk Point subgroup have collapsed in the area northeast of the dissolution edge of the Cold Lake and Upper Lotsberg Salt members, and that only the upper part of the Ernestina Lake Formation can be traced in the subsurface beyond the dissolution edge of the Upper Lotsberg Salt.

In west-central Saskatchewan, the Lower Elk Point subgroup is present in the subsurface northwest of the Meadow Lake Escarpment (see van Hees, 1958; Grayston et al., 1964). The interbedded succession of redbeds, anhydrite, dolostone and sandstone, which unconformably overlies Cambrian or Early Ordovician sandstone, was described by van Hees (1956) as the "Meadow Lake Beds". He used the section between depths of 610.8 and 697.9 m (2004 and 2290 ft) in the Seaboard Meadow Lake Crown No. 1 well (located in Saskatchewan in Lsd. 13, Sec. 21, Tw. 61, Rge. 15, west of the 3rd meridian) as reference (see Fig. 33). Subsurface correlations by van Hees (1958) indicate that the "Meadow Lake Beds" underlie the

Figure 47. Photograph of a regressive sequence in anhydritic rocks, Bear Rock Formation (true to scale).

These five core samples form a continuous succession. The base of the succession lies at the lower right, the top at the upper left. IOE Trail River well; Lat. 62°02'59"N, Long. 121°32'13"W; District of Mackenzie; depth interval between 1614 and 1616 feet (492.0 m).

The basal unit is a light brown, cryptocrystalline, anhydritic dolostone. It overlies a thin, dark greenish grey, pyritic shale bed with a sharp contact, and comprises a succession of wackestones and mudstones. The wackestones contain unsorted, irregularly shaped, dolomitic mud-clasts, coarse anhydrite grains, and anhydrite-filled, fenestral vugs. The light coloured mudstone beds are dolomitic; the dark coloured ones are anhydritic. Bedding is distorted by compaction.

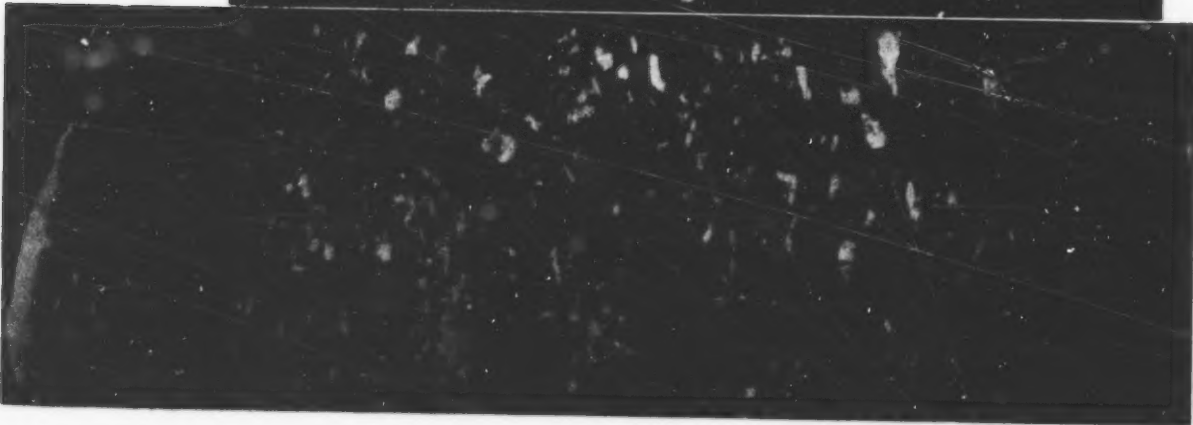
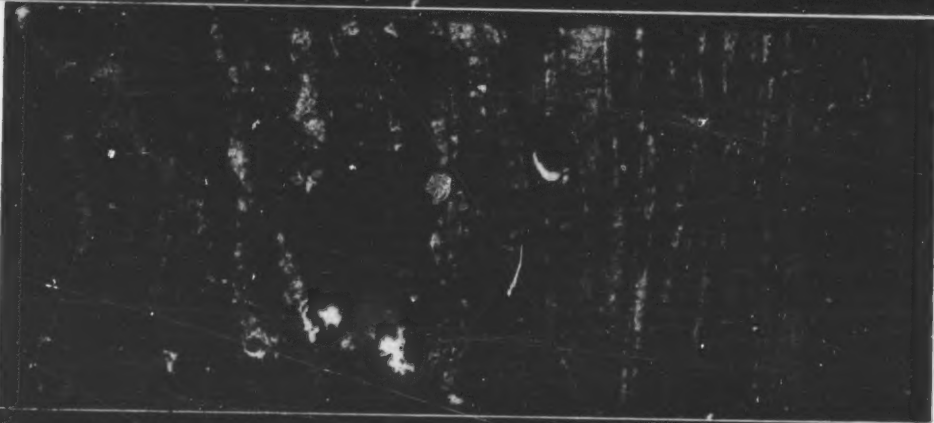
The basal unit is overlain by a very dark grey and grey, nodular-bedded anhydritic-mudstone. In the lower part of the second column, this unit includes light coloured, dolomitic layers. It is sharply overlain by a thin, greyish brown, anhydritic wackestone bed containing dark, irregularly shaped anhydrite nodules.

The upper part of the second column from the right is greyish brown and wavy bedded. It consists of light coloured layers of dolomite-mudstone and dark layers of secondary anhydrite. The mudstone also includes scattered, dark, nodular clusters of subhedral anhydrite. It is cut by vertical anhydrite veins.

The lower part of the third column is a succession of greyish brown, anhydritic and light brown dolomitic mudstone beds. In the upper part, anhydrite is prominently present as dark nodular beds composed of coarse crystal aggregates. Some aggregates are partly recrystallized into white, gypsiferous nodules.

The sample on the left side of the photograph is a very dark grey, nodular-mosaic anhydrite. It overlies the light coloured dolomite-mudstone with a sharp contact that may represent a hiatus.

2 cm



equivalents of the Contact Rapids Formation. In the reference well, the interbedded succession of anhydrite, dolostone and limestone, between depths of 601.8 and 633.9 m (2004 and 2080 ft), corresponds to the upper part of the Ernestina Lake Formation. It locally contains ostracodes of Early or early Middle Devonian age. The interval between depths of 633.9 and 697.9 m (2080 and 2290 ft) is composed of redbeds and includes a 3 m (10 ft) thick basal member of reddish coloured, conglomeratic sandstone and anhydrite. This interval is the equivalent of the "Basal Red Beds" unit of Sherwin (1962).

Upper Elk Point evaporites

The evaporites of the Upper Elk Point subgroup include thick and extensive deposits of halite and anhydrite. Redbeds occur as interbeds in the upper part of the subgroup.

The salt deposits of the Prairie Evaporite and Dawson Bay formations occur in the central part of the Elk Point Basin. Along the southwestern margin of the Elk Point Basin, the salt beds are replaced by a nearshore, argillaceous facies which onlaps the Western Alberta Ridge and the southeastern part of the Peace River Arch (see Fig. 48). In the northwestern part of the Elk Point Basin, anhydrite is the dominant lithology. The anhydritic facies (Muskeg Formation) onlaps the northern flank of the Peace River Arch and grades northwestward into carbonates which include reefal beds (Presqu'île Barrier). Northwest of the Presqu'île Barrier, the age equivalents of the Presqu'île Barrier consist of isolated reefal carbonate mounds (the Horn Plateau Formation) or beds of dark, fossiliferous limestone and marl (Fig. 23).

The orderly distribution of the five facies described above suggests that the salt is of marine origin, and accumulated behind a barrier of interbedded reefal carbonates and related deposits. The influence of the pre-Devonian paleotopography on the thickness and distribution of the Upper Elk Point deposits is evident, but is not as prominent as in the Lower Elk Point deposits. However, there are three other important features that have modified the regional facies pattern described above. The first is the presence of local, reefal, carbonate mounds in the upper part of the Keg River and Winnipegosis formations. These influenced the deposition of the evaporites in the lower part of the Prairie Evaporite and Muskeg formations. The second is the presence of marine, fossiliferous carbonates in the Dawson Bay Formation, which influenced the deposition of the Hubbard Salt Member. The third feature has resulted from both the Prairie Evaporite and Hubbard salt beds having been partly leached from the subsurface so that the present distribution of the salt beds is not as it originally was.

The Upper Elk Point subgroup was mapped by Grayston et al. (1964, Fig. 5-5) who recognized four facies: evaporites, clastics, carbonates, and reefal carbonates. Their isopach map indicates that the subgroup is over 304.8 m (1000 ft) thick in northeastern Alberta and south-central Saskatchewan. The evaporitic deposits of the upper Elk Point include four relatively well established map units, the Ratner Member of the Winnipegosis Formation, the Prairie Evaporite Formation, the Muskeg Formation, and the Hubbard Evaporite Member of the Dawson Bay Formation.

Ratner Member, Winnipegosis Formation. The term Ratner Member was proposed by Reinson and Wardlaw (1972) for a unit consisting of finely laminated, argillaceous and bituminous, anhydritic carbonates. According to Reinson and

Wardlaw (1972), the member occurs in the subsurface of Saskatchewan northeast of Saskatoon, below the Whitkow Salt, and was described as a part of the Upper member of the Winnipegosis Formation. The laminated carbonates were first described by Jones (1963). He considered them to be equivalent to the much thicker Winnipegosis carbonate mound facies. He noted the presence of anhydrite in the upper part of the laminated carbonates, and mapped these anhydritic beds together with the Prairie Evaporite Formation.

The Ratner Member was mapped in more detail by Wardlaw and Reinson (1971) in the subsurface northeast of Saskatoon. They studied the member from several cored sections and recognized eight units. These units remain remarkably constant in thickness and can be traced over a distance of about 160.9 km (100 mi). The units are either calcitic, dolomitic, or anhydritic. The calcitic and dolomitic units are parallel laminated, and contain much bituminous material. The anhydrite units consist of interbedded dolomite and anhydrite. The anhydrite is nodular, disturbed-nodular, enterolithic, or mosaic.

The anhydritic facies was described in detail by Shearman and Fuller (1969) from a core of the California Standard Ratner well, located in Lsd. 1, Sec. 15, Tw. 48, Rge. 17, west of the 2nd meridian. In this core, the anhydrite occurs in two types. The first type is nodular- or contorted-bedded, and is in places replaced by calcite (see also Fuller and Porter, 1969; Fig. 14a). The calcitized anhydrite and the dolostone interbedded with bituminous laminae are locally intruded, and partly replaced, by the second type of anhydrite, which is not calcitized. The second type of anhydrite was apparently not deposited as a sediment but grew displacively.

Thin, laminated equivalents of the Ratner Member occur locally below the Whitkow Member in south-central Saskatchewan. In Figure 49, these beds are shown as the laminated facies of the Upper member of the Winnipegosis Formation. Examples of the laminated facies are shown in figures 50a, b, and c.

Prairie Evaporite Formation. The term Prairie Evaporite was introduced by Baillie (1953) for a thick unit of salt and minor anhydrite in the subsurface of southern Saskatchewan. The type section is located between depths of 1326.4 and 1524.0 m (4352 and 5000 ft) in the Imperial Davidson No. 1 well, located in Lsd. 16, Sec. 8, Tw. 27, Rge. 1, west of the 3rd meridian. Because borehole logs and samples are missing, and only two short cores are available for study, Holter (1969) established a reference section in the White Rose et al. Drake well, located in Lsd. 4, Sec. 29, Tw. 32, Rge. 22, west of the 2nd meridian. This section is shown in Figure 49.

Holter (1969) included in the Prairie Evaporite Formation all beds situated between the Lower Redbed member of the Dawson Bay Formation above and the top of the Winnipegosis Formation (as defined by Jones, 1963) below. The formation is an interbedded succession of halite, sylvite, bedded anhydrite, and minor anhydritic dolostone. The base of the formation was selected at the lowest occurrence of bedded anhydrite, above the carbonates of the Winnipegosis Formation. The top was chosen at the base of the red and green mottled, dolomitic shale of the Dawson Bay Formation.

The Prairie Evaporite Formation was mapped in Manitoba by Bannatyne and McCabe (1966), in Saskatchewan by Holter (1969), and in central Alberta by Hamilton (1971). Their maps were used to construct the facies and isopach

map of the Prairie Evaporite Formation in Manitoba and Saskatchewan in Figure 51. In Alberta, the interval mapped in Figure 52 combines the Prairie Evaporite and the equivalent of the Dawson Bay Formation so that values approximately 15.2 m (50 ft) higher are obtained.

In Figure 51, the Prairie Evaporite Formation reaches a maximum thickness of over 213.4 m (700 ft) in a small area east of Saskatoon. The isopachs show a general increase in thickness from southeast to northwest. This is a depositional feature. The rather sharp decrease in thickness, from 182.9 m (600 ft) to less than 30.5 m (100 ft) southwest of the approximate northern edge of halite, is due to leaching of salt from the subsurface. Northeast of the approximate northern edge of halite, the Prairie Evaporite Formation is represented by anhydritic and argillaceous beds. The available subsurface information suggests that this anhydritic facies disappears farther northeastward. The northeastern limit of the anhydritic facies was mapped by Holter (1969, Fig. 10) as the northern limit of anhydrite.

The Elk Point Basin is shown on structural cross-section F₁-F₂ (Fig. 34). This section confirms the presence of a depositional edge along the southwestern margin. It shows the collapse of the beds overlying the Prairie Evaporite Formation along the northern edge of the halite and indicates the absence of anhydrite farther northeast. It is possible that originally the Prairie Evaporite Formation in this area did not include much anhydrite, but it is equally possible that the anhydrite changed to gypsum and was leached from the shallow subsurface at a later date. The collapse structures (shown in Figure 34) in the subsurface south of Saskatoon and Regina indicate that, originally, salt must have been present there. The cross-section also shows that the Prairie Evaporite Formation is anomalously thin in the areas where it overlies Winnipegosis carbonate mounds. These anomalously thin values were omitted before the construction of the isopach map (Fig. 51).

The Prairie Evaporite Formation is traced northwestward in figures 27, 28, and 29. Several facies changes which involve the Prairie Evaporite Formation are depicted. Southeast of Saskatoon (as illustrated in Fig. 29), the contact between the Prairie Evaporite and the Winnipegosis formations steps downsection because of a facies change from carbonates to evaporites. Southeast of this facies change, the carbonate mounds of the Upper member of the Winnipegosis Formation are surrounded and, in places, overlain by anhydritic deposits. The size of the carbonate mounds is unknown and the interpretation in Figure 29 and on the isopach map by Holter (Fig. 51) suggests that they are small. Gendzwil (1978) mapped the facies transition between carbonates and evaporites with the aid of seismic profiles and found that the mounds vary in width from 1 to 8 km (0.6 to 4.9 mi).

An informal subdivision of the Prairie Evaporite Formation was introduced by Holter (1969). He recognized a lower salt unit and an upper salt unit, and described three potash-ore members in the upper salt unit. The lower salt unit was formally subdivided by Reinson and Wardlaw (1972) into the Whitkow and Shell Lake members. In the following discussion, the Prairie Evaporite Formation is subdivided into three members, which are, in ascending order, the Whitkow, Shell Lake, and Leofnard (see Fig. 49). The potash members of Holter (1969) are reduced in rank to subunits of the Leofnard Member.

Whitkow Member. The Whitkow Member was defined by Reinson and Wardlaw (1972) in the subsurface of Saskatchewan, in the Tidewater Bryce Lake Crown No. 1

well, located in Lsd. 1, Sec. 14, Tw. 25, Rge. 16, west of the 2nd meridian (see structural cross-section A₄-A₅, Fig. 29). It consists of semi-translucent, coarsely crystalline halite (Fig. 50h) with interbeds of light grey, nodular-mosaic, and mosaic anhydrite (Fig. 50d, e). It includes a basal unit of dolomitic anhydrite (see Fig. 50c). Locally, remnants of the original crystal fabric are visible in the salt (see Fig. 50f). This type of halite was described by Wardlaw and Schwerdtner (1966) and named "chevron halite".

The Whitkow Member is locally present in Saskatchewan and east-central Alberta, where it forms the basal unit of the Prairie Evaporite Formation in the central part of the Elk Point Basin (see structural cross-sections A₃-A₄ and A₄-A₅, figs. 28, 29). It overlies the laminated facies of the Upper member of the Winnipegosis Formation and is underlain by the Shell Lake Member. The relationships between the Whitkow and Shell Lake members and the Winnipegosis Formation are shown in more detail in Figure 49. In the east side of the stratigraphic section illustrated in Figure 49, the Whitkow Salt is equivalent to the lower part of the carbonate mound facies of the Winnipegosis Formation, and is separated from the carbonates by a facies consisting of interbedded anhydrite and anhydritic dolostone; the "undifferentiated Shell Lake - Whitkow" facies. Reinson and Wardlaw (1972) described a similar situation in the area northeast of Saskatoon.

On the west side of the stratigraphic section illustrated in Figure 49, the upper part of the Winnipegosis Formation cannot be subdivided into a thin, basinal laminated facies and a carbonate mound facies. It is a unit of rather uniform thickness referred to as the lagoonal platform facies. The interpretation shown suggests that the Whitkow Salt is equivalent to the lagoonal platform facies of the upper part of the Winnipegosis Formation, and it is postulated that the salt and carbonates are separated from each other by an anhydritic facies similar to the "Undifferentiated Shell Lake - Whitkow" facies of Reinson and Wardlaw (1972). This interpretation is also shown on structural cross-section A₄-A₅ (Fig. 29).

The Whitkow Member is locally present in east-central Alberta. In the Texan CS Horse River well (located in Lsd. 16, Sec. 27, Tw. 85, Rge. 11, west of the 4th meridian) and in the Pan Am A-1 Telegraph well (located in Lsd. 6, Sec. 30, Tw. 86, Rge. 13, west of the 4th meridian) the salt beds are more than 30 m thick, but the basal anhydritic beds are thin or absent (see Fig. 53). The correlations shown in Figure 53 indicate that the Whitkow Salt is in lateral contact with the upper part of the Winnipegosis Formation. The lithology of the Winnipegosis Formation in the cores of the Horse River, Telegraph, and Algar River wells described by Corrigan (1965, p. 108-110) suggests that the Whitkow Salt overlies a pre-existing topographic feature. The Winnipegosis Formation in the core of the Horse River well consists of dark coloured, bioturbated limestone with fossilized remains of foraminifera, "calcspheres", ostracodes, and cricoconarids. Corrigan (*ibid.*) noted the presence of laminated beds just below the halite. In the Telegraph and Algar River wells, the Winnipegosis Formation consists of bioturbated, crinoidal carbonates interbedded with dark, bituminous, unfossiliferous and laminated carbonates. The upper part of the Winnipegosis Formation in the two wells includes remains of stromatoporoids and corals. The lithology and fossils present suggest that the Winnipegosis Formation in these wells is a marine deposit and it is unlikely that it was deposited at the same time as the salt. It is more likely that the lower part of the Shell Lake Member is a facies equivalent of the Whitkow Salt.

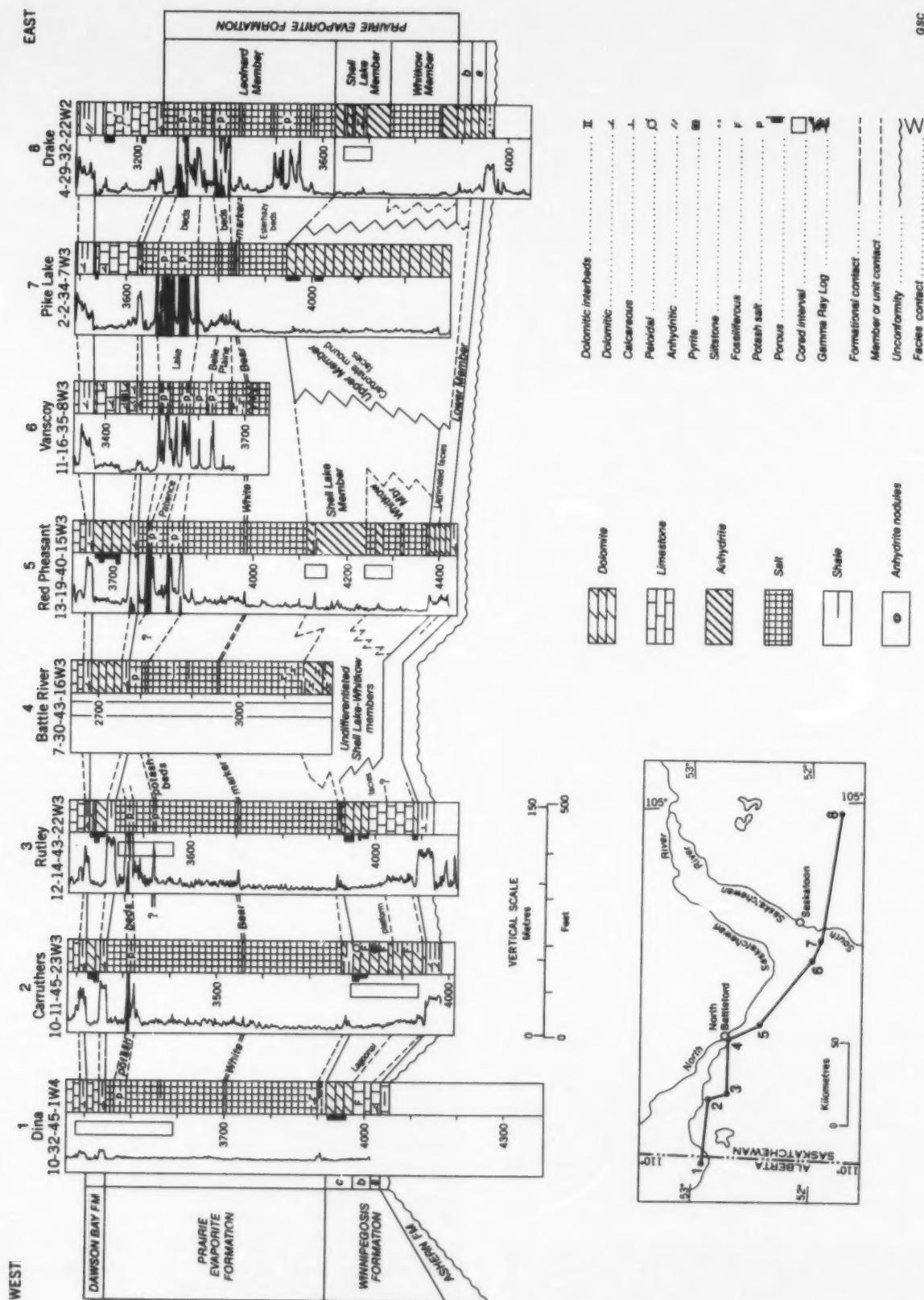


Figure 48. Stratigraphic cross-section, Elk Point Group, southern Saskatchewan.

A similar stratigraphic situation, in which the Whitkow Member is present in the Bear Rodeo No. 1 well (Lsd. 8, Sec. 20, Tw. 89, Rge. 9, west of the 4th meridian) but is absent in the nearby wells, is shown in Figure 39. The lithology of the Winnipegosis Formation in these wells was described by Corrigan (1975, p. 112-115).

It is impossible to map the areal extent of the Whitkow Member with the amount of control available. The distribution of the member is inversely related to the distribution and thickness of the lagoonal-platform and carbonate mound facies of the upper member of the Winnipegosis Formation. These two facies were mapped by Grayston et al. (1964, Fig. 5-11c) on a regional scale as fringing carbonate bank and patch reefs. The Whitkow Member is present in the area between the patch reefs and carbonate banks and varies in thickness between 0 and 68.5 m (225 ft).

Shell Lake Member. The Shell Lake Member, as defined by Reinson and Wardlaw (1972) in the White Rose et al. Drake well, located in Lsd. 4, Sec. 29, Tw. 32, Rge. 22, west of the 2nd meridian (see Fig. 49), overlies the Whitkow Member and includes three dolomitic beds. In areas where the Whitkow Salt is absent, the Shell Lake Member either overlies the Winnipegosis Formation or forms the upper part of the "undifferentiated Shell Lake - Whitkow" beds (see Reinson and Wardlaw, 1972; Fig. 1). Correlations in the subsurface suggest that the basal anhydritic unit of the Prairie Evaporite Formation in central Alberta is in mappable continuity with the Shell Lake Member (see figs. 27, 28, 29). This anhydritic unit is herein considered as part of the Shell Lake Member.

The relationships in Saskatchewan between the Shell Lake, the Whitkow, the "undifferentiated Shell Lake - Whitkow" beds of the Prairie Evaporite Formation, and the carbonate mound facies or the lagoonal-platform facies of the Upper member of the Winnipegosis Formation, are shown in Figure 49. The Shell Lake Member consists of light grey, nodular-bedded, dolomitic anhydrite (see Fig. 54b), or anhydrite interbedded with light brown, anhydritic dolostone, and dolostone. The anhydritic dolostone is very finely to finely peloidal, commonly laminated, and, in places, includes halite cement (see figs. 50g, 54e). In the Saskatoon area, the Shell Lake Member includes a distinctive lithologic marker, named the Quill Lake marker beds (Reinson and Wardlaw, 1972). The Quill Lake marker beds consist of laminated and peloidal, in places pisolitic, dolostone; locally including poorly preserved *amphipora*-like fossils and stromatolites (Wardlaw and Reinson, 1971). The Quill Lake marker beds may be equivalent to the pisolitic beds and interbedded stromatolitic, fossiliferous and peloidal beds, which occur near the top of the Winnipegosis carbonate mounds just below the Shell Lake Member. In the areas where the Shell Lake Member overlies the Winnipegosis carbonate mound facies, the lower contact is transitional. The uppermost carbonate beds of the Winnipegosis Formation are partly replaced by anhydrite and salt; anhydrite or gypsum filled fractures and cavities occur in the carbonate.

The contact between the Shell Lake and Whitkow members is fairly sharp. The lithology of the "undifferentiated Shell Lake - Whitkow" beds is similar to the lithology of the Shell Lake Member described previously (see Fig. 54g). It includes, in the upper part, an argillaceous interval with a thin conglomerate (see Fig. 54d). The correlations shown in Figure 49 suggest that the upper part of the "undifferentiated Shell Lake - Whitkow" beds is a facies equivalent of the lower part of the Leofnard Member.

In southwestern Saskatchewan and central Alberta, the Shell Lake Member is a thin unit, consisting of argillaceous

and anhydritic beds, which overlies the lagoonal-platform facies of the Winnipegosis Formation. Typical sections are shown in Figure 49 (west side). In southwestern Saskatchewan and central Alberta, the member consists of light brown, finely to medium peloidal dolostone with anhydrite-filled fenestral voids (see Fig. 54c). Anhydrite also occurs as nodular interbeds similar to those shown in Figure 54b. In the upper part of the Shell Lake Member, pale greenish grey, dolomitic anhydrite, and greenish grey, argillaceous dolostone interbeds, similar to those shown in the upper part of Figure 54a, are common. The contact with the overlying Leofnard Salt is fairly sharp (see Fig. 54h, i).

In Saskatchewan, the Shell Lake Member varies in thickness between 0 and 35 m (115 ft). The "undifferentiated Shell Lake - Whitkow" beds attain a maximum thickness of 70.7 m (232 ft) in the Can. Gridoil Kenasto well (located in Lsd. 9, Sec. 29, Tw. 30, Rge. 1, west of the 3rd meridian).

In west-central Alberta, the Shell Lake Member is a distinct map unit, but northwest of Fort McMurray it cannot be recognized because of the regional facies change between the Prairie Evaporite and Muskeg formations. This facies change is shown in Figure 28. The stratigraphic relationships between the Shell Lake Member and the Whitkow and Leofnard members are shown in Figure 53. On the stratigraphic cross-section, the Shell Lake Member west of the Algar River well is interbedded with argillaceous beds. The argillaceous interbeds increase in thickness and number in a westward direction (approaching the Peace River Arch), and it can be demonstrated, with the aid of an anhydritic marker bed in the basal part of the Shell Lake Member, that the Shell Lake Member is found at progressively higher stratigraphic levels from east to west, because of onlap against the Peace River Arch.

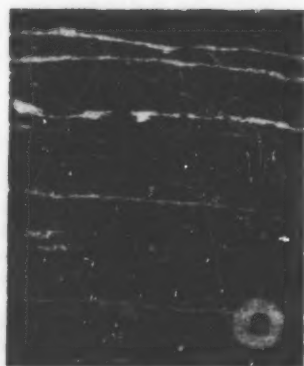
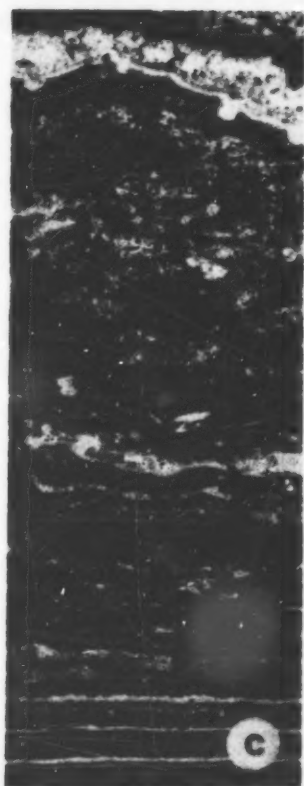
In the ARCO IOE Utikuma well, located in Lsd. 4, Sec. 2, Tw. 83, Rge. 9, west of the 4th meridian, the near-shore, argillaceous equivalents of the Shell Lake Member (Muskeg Formation, unit A on Fig. 53) consist of greenish grey dolomitic and anhydritic shale, light brown, anhydritic dolostone, and light grey anhydrite. The dolostone beds contain microscopic fragments of plants (*Charophyta*?) in addition to mud clasts, and anhydrite-filled casts of halite crystals (see Fig. 55a, b, c, d, e). The Shell Lake Member in Alberta varies between 3.6 and 14.0 m (12 and 46 ft). The "undifferentiated Shell Lake - Whitkow" beds attain a maximum thickness of 39.0 m (128 ft) in the FPC et al. Birch Hills well, located in Lsd. 10, Sec. 36, Tw. 98, Rge. 21, west of the 4th meridian (see Fig. 27).

Leofnard Member. The name Leofnard Member was introduced by Jordan (1968) for the upper part of the Prairie Evaporite Formation in the subsurface east of Saskatoon, Saskatchewan. It is proposed to use this name for the interbedded succession of salt, anhydrite, and minor dolostone and shale in the Prairie Evaporite Formation, situated between the Shell Lake Member below and the Dawson Bay Formation above. The interval between depths of 1053.7 and 1187.2 m (3457 and 3895 ft) in the Verbata No. 2 well, located in Lsd. 7, Sec. 24, Tw. 41, Rge. 24, west of the 3rd meridian, southeast of Lloydminster, in Saskatchewan, is designated as the type section. In this well, the Prairie Evaporite Formation was completely cored.

The Leofnard Member constitutes the bulk of the Prairie Evaporite Formation in Manitoba, southern Saskatchewan, and east-central Alberta, and reaches a maximum thickness of 207.3 m (680 ft) in east-central Alberta. It is almost everywhere underlain by the Shell Lake Member. In Manitoba, Saskatchewan and east-central

Figure 50. Core samples of Upper Elk Point evaporites (true to scale, except where indicated).

- a. Limestone "laminite". Very dark grey and brown calcite layers are interbedded, in a nodular structure, with very light grey anhydrite. See description of thin section in d. Ratner Member, Winnipegosis Formation; Tide water Allen Crown well; 16-11-33-1W3, Saskatchewan; depth 4142 feet (1262.5 m).
- b. Thin section of sample a (magnification 2.5x). Dark layers are cryptocrystalline calcite, grey layers are fine- to medium-crystalline calcite, and light grey areas are very fine, crystalline anhydrite. The calcite layers are separated from each other by dark brown, bituminous partings. Comparison with Figure 18a suggests that the sample is a stromatolite.
- c. Dolomite "laminite" grading upward into nodular, dolomitic anhydrite. Light grey layers are light brown, microcrystalline dolomite; grey material is anhydrite; and dark laminae are bituminous shale. In the basal part of the sample, light coloured layers are composed of very fine dolomite peloids cemented by anhydrite, and the grey layers are anhydrite-mudstone. Arrow points to an area completely replaced by anhydrite. Above the arrow, the amount of anhydrite cement increases and the distance between the bituminous shale partings becomes larger. In the upper part of the sample, the anhydrite cement has formed irregular nodules and the light coloured dolomitic layers are distorted. This indicates that the nodules are a secondary deposit. Anhydrite unit; Whitkow Member; Prairie Evaporite Formation; Dome Provo Foam Lake well; 15-29-30-13W2; Saskatchewan; depth 3706 feet (1129.6 m).
- d. Light grey, fine- to medium-crystalline, massive anhydrite with light brown layers and light coloured inclusions resembling mudstone granules. Sample is an anhydritized sediment. Whitkow Member, Prairie Evaporite Formation; Pheas. Banff Red Pheasant well; 13-19-40-15W3; Saskatchewan; depth 4266.5 feet (1300.4 m).
- e. Light grey, finely crystalline, mosaic anhydrite with light brown, bituminous layers and very light grey, dolomitic inclusions. Bed is underlain and overlain by halite and both contacts are visible in sample. The very light grey, dolomitic layers in the lower and upper parts of the sample are very finely peloidal and are of sedimentary origin. The laminated, triangular and quadrangular structures in the central and upper part of the sample are reminiscent of chevron halite (see Fig. 50f, d). Whitkow Member, Prairie Evaporite Formation; Pheas. Banff Red Pheasant well; depth 4253 feet (1296.3 m).
- f. Chevron halite. Clear halite with very light grey laminae showing chevron pattern. Whitkow Member, Prairie Evaporite Formation; Pheas. Banff Red Pheasant well; depth 4273.5 feet (1302.6 m).
- g. Light brown, fine to coarsely peloidal dolostone with halite cement overlies greenish grey, discontinuously laminated, slightly dolomitic anhydrite-mudstone. Shell Lake Member, Prairie Evaporite Formation; White Rose et al. Drake; 4-29-32-22W2; Saskatchewan; depth 3651.5 feet (1113.0 m).
- h. Whitkow Salt in the Pan Am A-1 Telegraph well, 6-30-86-13W4, Alberta, core 3, boxes 5 and 8. Light grey, semi-translucent halite beds with chevron crystals are regularly interbedded with wavy, light grey, dolomitic anhydrite.



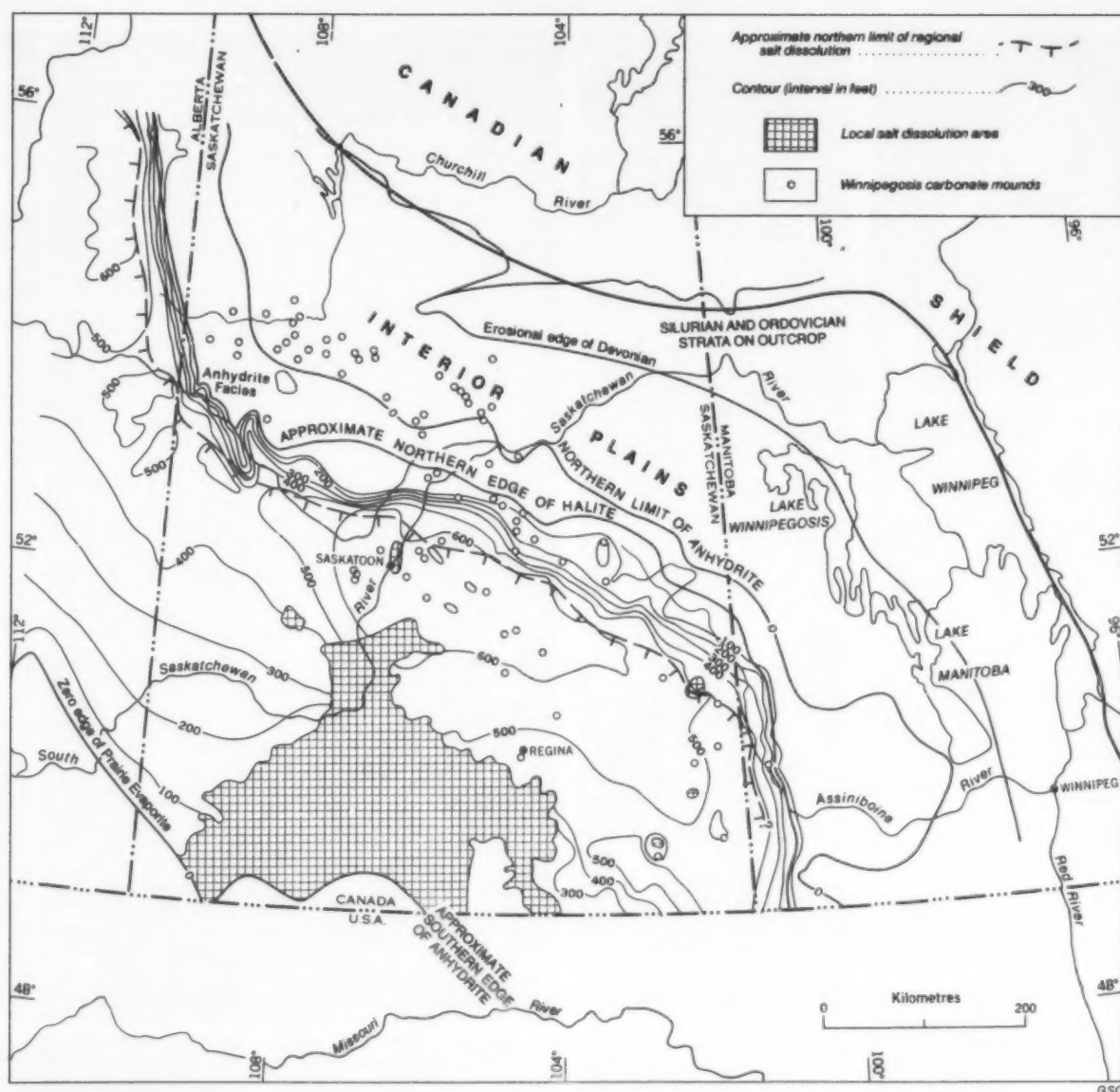


Figure 51. Facies and isopach map of the Prairie Evaporite Formation in Saskatchewan and Manitoba.

Alberta, the Leofnard Member is overlain by the lower redbed unit of the Dawson Bay Formation. In northeastern Alberta it is overlain by interbedded anhydrite and dolostone of the Muskeg Formation. Depositional limits of the Leofnard Salt can be mapped in southwestern Saskatchewan and central and northern Alberta (see figs. 51, 52).

The Leofnard Member includes a useful marker bed in the middle. In Saskatchewan, this unit was named the "White Bear marker beds" (Holter, 1969; Fig. 4). Klingpor (1969) referred to it as the "Muskeg 40" marker. The White Bear marker is one of several tongues of interbedded dolostone and anhydrite which merge with the Muskeg Formation in northern Alberta. The presence of a distinctive shale bed in the basal part of the marker sets it apart from the other Muskeg anhydrite tongues in the Leofnard Member. The White Bear marker subdivides the Leofnard Member into an

upper and lower part. In southeastern Saskatchewan and Manitoba, this subdivision is not apparent because the White Bear marker is thin and difficult to recognize on borehole logs.

Lithology. In the type section (the Verbata No. 2 well, see Fig. 29), the lower part of the Leofnard Member is composed of relatively pure, semi-translucent, light rusty brown, and greenish grey halite. The lower contact with the Shell Lake Member is fairly sharp and marked by a thin transitional interval of mixed dolomitic shale and halite (see Fig. 54i). This is overlain by relatively pure, semi-translucent, light grey halite, similar to the samples shown in Figure 50h. The halite includes many irregular and discontinuous laminae and interbeds of dolomitic and anhydrite shale or argillaceous anhydrite. This light grey

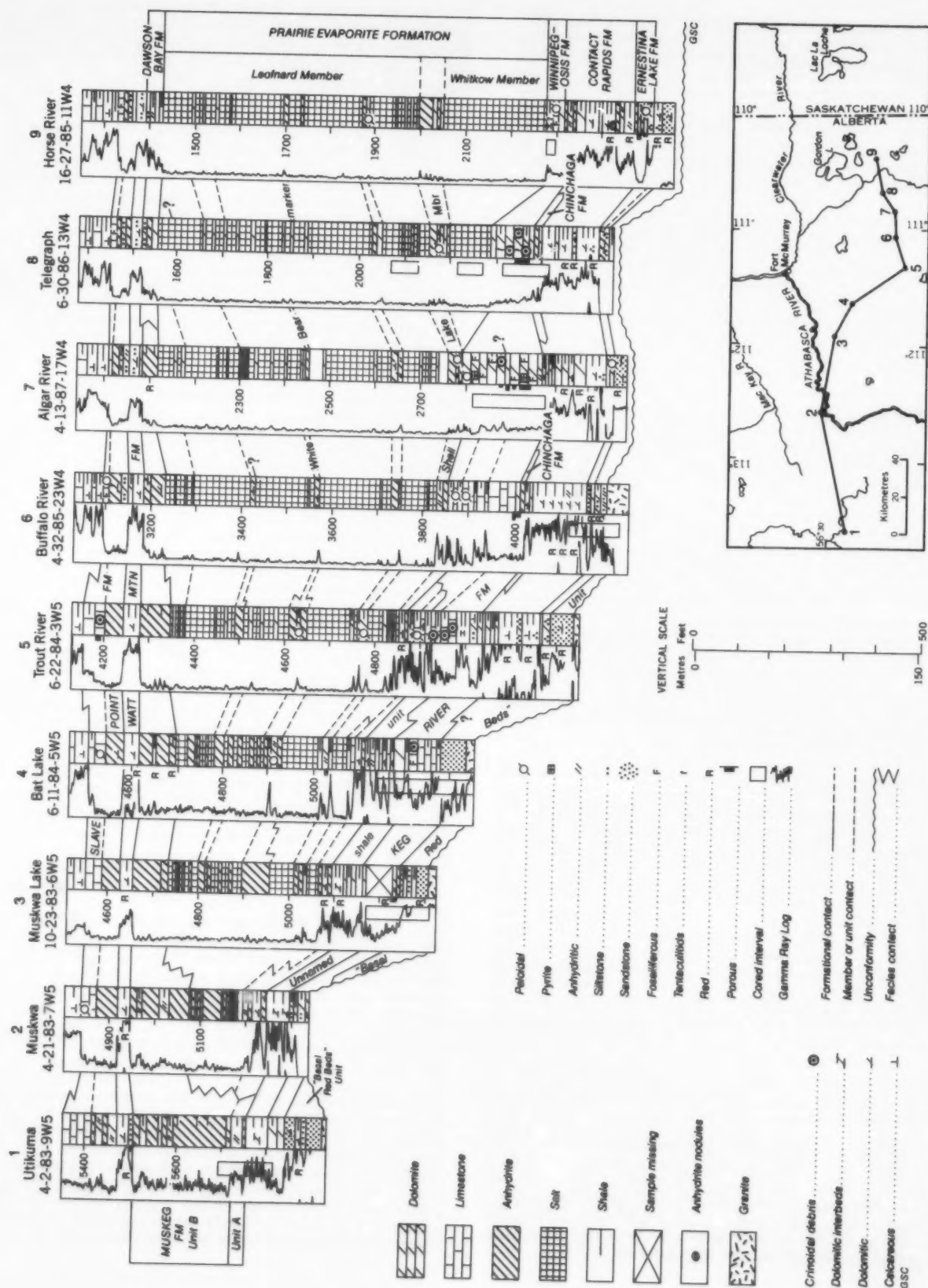


Figure 53. Stratigraphic cross-section, Upper Elk Point subgroup, east-central Alberta.

halite grades upward into a banded succession of grey, light brown, and greenish grey halite, interbedded with thin, greenish grey shale, light grey anhydrite or light reddish brown shale. It is recrystallized and crystals vary in diameter between 0.5 and 1 cm. The reddish brown colours in the salt are due to clay inclusions in the crystals and to the presence of thin shale partings. In places, the reddish brown halite beds in the Verbata No. 2 cores include red-brown coated vugs. The vugs probably represent the remains of sylvite or carnallite crystals.

The basal shale beds of the White Bear marker overlie the lower part of the Leofnard Member with a sharp and irregular contact. This contact and the polygonal dissolution fractures in the underlying halite are visible in the Cominco Vanscoy mine south of Saskatoon (see Fig. 56a, b). They were described by Price and Ball (1973, Fig. 7). A similar sharp contact is present in the Verbata No. 2 well at a depth of 1128.0 m (3701 ft).

The basal, dark greenish grey, siliceous shale or claystone of the White Bear marker grades upward into a very light and greenish grey, laminated, halite-impregnated dolostone (Fig. 56b, c). In the upper part, the dolostone is partly replaced by brown halite or anhydrite (Fig. 56b, d). The White Bear marker is about 75 cm thick in the Cominco Vanscoy mine and 1.2 m thick in the Verbata No. 2 well.

In the Verbata No. 2 well, the White Bear marker is sharply overlain by an interbedded succession of semi-translucent halite and light grey anhydrite. The anhydritic beds are undulatory and, in the Cominco Vanscoy mine, the lower surface of the beds is commonly rippled (see Fig. 56e, f). This light coloured unit is about 6 m (20 ft) thick and grades upward into a succession of semi-translucent, orange, grey, and greyish brown halite, interbedded with greenish grey, dolomitic or anhydritic shale beds up to 2 cm thick. The halite beds contain scattered, reddish brown sylvite crystals and, in places, substantial amounts of reddish brown clay. In the Cominco Vanscoy mine, some reddish brown shale beds include polygonal syneresis cracks (Dellwig, 1972) filled with halite (see Fig. 57c).

The upper part of the Leofnard Member in the Verbata No. 2 well probably includes an interval rich in potash salts between depths of 1055.5 and 1062.8 m (3463 and 3487 ft). This interval was removed from the core boxes by the operator for chemical analysis. Equivalent strata in a nearby well, the BA Cutknife Rutley well (located in Lsd. 12, Sec. 14, Twp. 43, Rge. 22, west of the 3rd meridian), include reddish brown beds composed of a coarse crystalline mixture of sylvite and halite, rusty brown beds of semi-translucent halite, and thin beds of red-brown, dolomitic shale. These potash-rich salt beds were also cored in other wells and samples are shown in Figure 57 (a, d, e). In the lower part of the sylvite-rich interval are two thin beds containing between 40 and 50 per cent carnallite. The upper carnallitic bed, at a depth of 1072.6 m (3519 ft), shows as a prominent marker on the gamma ray curve (see Fig. 49). In the Cominco Vanscoy mine, the red-brown, dolomitic shale beds and the potash salt beds include large polygonal structures outlined by sylvite crystals (see Fig. 57b). These polygons resemble large mudcracks (Baar, 1972).

The potash-rich salt beds are overlain by reddish brown beds without potash salt but with many interbeds of reddish brown shale (see Fig. 57f). The contact between the Leofnard Member and the overlying redbeds of the Dawson Bay Formation is fairly sharp in the Verbata No. 2 well, and is located at the top of the highest salt bed. The contact is also present in the core sample shown in Figure 57g.

In southeastern Saskatchewan and Manitoba, the Leofnard Member includes potash-rich salt beds below the White Bear marker. These beds were mapped by Holter (1969 and 1972) and Bannatyne and McCabe (1966) as the Esterhazy Member of the Prairie Evaporite Formation. Holter (1969 and 1972) also mapped and described the potash-rich beds in the upper part of the Prairie Evaporite Formation, and recognized two units, the Belle Plaine and the Patience Lake members. In this report, the three potash-rich units are regarded as sub-members of the Leofnard Member (see Fig. 49). The intervals rich in potash are easily mapped with the aid of gamma ray logs, and their presence is indicated on the structural cross-sections (figs. 29, 34) by black rectangles. In southeastern Saskatchewan and Manitoba, the absence of the White Bear marker, the effects of salt leaching along the northeastern and eastern edges of the Leofnard Member, and the variation in thickness and grade of the potash beds, make the correlation of individual potash beds with any of the three members somewhat subjective. For this reason, the writer did not correlate the potash-rich intervals shown in figures 29 and 34. In the area where the White Bear marker is present, the three potash beds are recognizable and the effect of salt leaching is apparent (see Fig. 49, Sec. 4).

The potash beds present in east-central Alberta near the Saskatchewan boundary are thin and of a low grade. They are not mappable with the aid of the gamma ray log. In central Saskatchewan, the potash beds are thick and of a high grade. They consist of a very coarse (0.6-1.2 cm) mixture of clear and milky halite, clear or red sylvite, clear or red carnallite, and minor amounts of carbonates, sulphate and clay. The red colour of the carnallite and the sylvite crystals is due to inclusions of hematite and goethite (Wardlaw, 1968). Sylvite and halite form a potash-rich mixture (sylvinite), which is composed of well or partly developed (euhedral to subhedral) halite crystals and irregular (anhedral) sylvite crystals (Schwerdtner, 1964). Samples of this lithology are shown in Figure 57 (d, e). Carnallite occurs as vertically oriented aggregates along boundaries of euhedral or subhedral sylvite or halite, which are partly replaced. Carnallite also occurs as dark red veins in the salt and interbedded claystone.

The potash beds contain red-brown or greenish grey shale as partings or fillings between the salt crystals (see Fig. 57d, e). In the Vanscoy potash mine, one bed also contains large, angular lithoclasts of shale.

Individual potash beds are remarkably continuous and can be traced in the subsurface over large distances. In general, the potash beds rich in carnallite underlie beds rich in sylvite and, in individual beds, carnallite is concentrated near the bottom and sylvite near the top. This situation greatly facilitates the operation of a potash mine, which is based on the handling of a particular grade of sylvinite. However, in some mines, the sylvinite ore deposits pass laterally into beds composed of carnallite. It was found that where red sylvite is in contact with red carnallite, the sylvite had replaced the carnallite and inherited the hematite inclusions (Wardlaw, 1968).

The continuity of the sylvinite deposits is also disturbed by the occurrence of irregular bodies of halite that are almost devoid of potash salt. Such bodies were named "salt horses" (McIntosh and Wardlaw, 1968), and, at some localities, they extend above and below the potash bed being mined. McIntosh and Wardlaw (1968) have suggested that the "salt horses" were formed locally by replacement. Sylvite in the potash beds reacted with brines saturated with sodium chloride and secondary halite precipitated as a result.

Depositional edge. The Leofnard Member thins in a southwesterly direction. The thinning coincides with a gradual replacement of salt by anhydrite. The western limit of the salt is a facies change and this facies change marks the edge of the Leofnard Member. A similar facies change occurs in northern Alberta where the interbedded halite and anhydrite facies grades northwestward into an interbedded succession of anhydrite and dolostone (see Fig. 27). This facies change does not coincide with regional thinning of the member.

The Leofnard Member in central Alberta was mapped by Hamilton (1971) as the "Prairie Evaporite Salt". Hamilton also described the salt from cores, analyzed the impurities, and established the depositional edge of the salt, which coincides with the edge of the Leofnard Member. According to Hamilton, the salt is commonly brown with hues of red, green, grey, or amber. White or colourless halite is uncommon. The chief impurities are shale, anhydrite, and dolomite. They are finely dispersed and are responsible for the various colours of the halite.

In the area southeast of Edmonton, near the depositional edge of the salt, the Leofnard Member is interbedded with anhydrite and dolostone. The equivalent strata southwest of the salt edge consist of greyish anhydritic dolostone, dolostone, limestone, and shale (see Belyea, 1959; Fig. 2), and are mapped in Figure 52 as the "Carbonate and anhydrite facies". North of Edmonton, the Leofnard Member is interbedded with anhydrite, dolostone, and greenish grey shale. The equivalent beds west of the depositional zero edge of salt consist of dolomitic shale, siltstone, sandstone, dolostone, and anhydrite (Hamilton, 1971; Fig. 4). These strata are difficult to separate from the underlying argillaceous equivalent of the upper part of the Winnipegosis Formation, and they are mapped together in Figure 52 as the "Shale and carbonate facies".

The basal part of the Leofnard Member (unit 3 of Corrigan, 1975) was cored in the Pan Am Chipewyan well, located in Lsd. 10, Sec. 16, Tw. 91, Rge. 18, west of the 4th meridian, and in the Pan Am A-1 Telegraph well, located in Lsd. 5, Sec. 30, Tw. 86, Rge. 13, west of the 4th meridian. Typical lithologies of the Chipewyan well are shown in Figure 58. They include semi-translucent halite beds (Fig. 58a, e), grey and light grey, mottled, "bioturbated" anhydrite (Fig. 58a), interbedded conglomeratic anhydrite, anhydritic mudstone, and fossiliferous anhydrite (Fig. 58b, c, d, e). The microfossils in the fossiliferous anhydrite are poorly preserved and are partly replaced by halite (Fig. 58b, c).

The western depositional edge of the Leofnard Member and the details of the facies change discussed above are shown in Figure 53. The basal part of the Leofnard Member, near the western edge of the Elk Point Basin, was cored in several wells. Two of these were discussed by Corrigan (1975, p. 245-246) and one was studied by the author. In the BA Bat Lake well (Lsd. 6, Sec. 31, Tw. 84, Rge. 7, west of the 5th meridian) the section is similar to that shown in Figure 53 for the Muskwa 4-21-83-7W5 well. The lower part of the Leofnard Member consists of interbedded, relatively pure, semi-translucent halite, intercalated with beds composed of a mixture of halite, anhydrite, or pale greenish grey shale (see Fig. 59a). In the anhydritic or shaly beds, halite occurs as inclusions, either filling desiccation fractures, interfragmental porosity or fenestral vugs (see Fig. 59a, b, c, d, g, h). In the impure salt beds, the halite crystals are mixed with anhydrite and the beds include chevron structures (see Fig. 59e). The nearshore equivalents of these strata consist mainly of anhydrite. These strata were cored in the ARCO

Utikuma 4-2-83-9W5 well (see Fig. 53, Muskeg Fm., Unit B) and consist of anhydrite, anhydritic shale, and thin anhydritized salt beds. The anhydritic shale beds contain remains of vegetal material.

The northern part of the depositional limit of the Leofnard Member is not easy to map. In northeastern Alberta the member includes several widespread units of interbedded anhydrite and dolostone. One of these units is the White Bear marker. The salt beds between anhydritic units decrease in number and thickness toward the northwest and are replaced by anhydrite and dolostone. This facies change is gradual and cuts across the isopachs, as shown in Figure 52. The zero edge of the salt marks the limit of the Leofnard Member and, in order to show the transitional character of the facies change, two other lines in Figure 52 delineate the areas in which the amount of salt varies between 0 and 10 or 10 and 40 per cent of the total thickness of the evaporites situated between the base of the Watt Mountain and the top of the Keg River (Winnipegosis) Formation.

The regional facies change between the interbedded halite and anhydrite facies of the Prairie Evaporite Formation and the interbedded anhydrite and dolostone facies of the Muskeg Formation, was described in some detail by Klingspor (1969). He traced the beds (here described as the White Bear marker of the Leofnard Member) across the facies change as the "Muskeg 40" marker in the Muskeg Formation of northwestern Alberta. He subdivided the evaporites into marker-bound members, making it possible to correlate individual anhydrite to halite cycles of the Prairie Evaporite Formation with the dolostone to anhydrite cycles in the Muskeg Formation.

The evaporitic cycles in the lower part of the Leofnard Member are difficult to trace in the subsurface northwest of Fort McMurray, because their continuity is broken by the presence of the Winnipegosis carbonate mounds and their evaporitic flank deposits. It is impossible to separate the evaporitic flank deposits from the regional, cyclic evaporites. Klingspor (1969), Bebout and Maiklem (1973), and Corrigan (1975) have described the cyclic evaporites and the evaporitic flank deposits in the lower part of the Leofnard Member from available cores. The salt beds are recrystallized and consist of semi-translucent halite with light grey, anhydritic laminae. The anhydritic beds include nodular-bedded, dolomitic anhydrite; distorted, nodular-mosaic anhydrite, and streaky laminated anhydrite containing remains of dolostone and dolomitic fossil fragments or pisoliths.

The evaporitic cycles in the upper part of the Leofnard Member are remarkably constant in thickness and can be correlated over great distances (see Busson, 1974; Klingspor, 1969, Fig. 14). However, the upper part of the Leofnard Member and the equivalent beds in the Muskeg Formation were not cored, and it is not possible to describe this facies change in any detail.

Dissolution edge. The northern limit of the Leofnard Member coincides with the approximate northern edge of halite, and the southern limit of the member in Saskatchewan follows the zero edge of the Prairie Evaporite Formation (see figs. 51, 52). The cross-sections in figures 31, 32, 33 and 34 indicate that the northeastern edge of the salt is abrupt and occurs at some distance southwest of the Cold Lake and Lutsberg Salt edges. The synclinal collapse structure in the Upper Devonian beds northeast of the salt edge suggests that the Leofnard Salt at one time covered a much larger area, but was later removed from the subsurface by

circulating groundwater during several periods of epeirogenesis (see Holter, 1969). The southern limit of the salt in Saskatchewan is shown in cross-section in Figure 34, and it is clear that, in the area south of Saskatoon, the limit of the salt is also a dissolution edge. However, farther southwestwards (see Fig. 34) the Leofnard Member is much thinner and the nature of the salt edge is difficult to establish. Holter (1969, Fig. 10) noted the presence of brecciated beds in strata equivalent to the Leofnard Member in the area southeast of the salt edge near Swift Current. According to him, the brecciated beds are a dissolution residue.

There are scattered areas in Saskatchewan where the salt of the Leofnard Member is locally missing. In Figure 51, these areas are indicated as isolated occurrences because there is not enough information available to link them with the principal dissolution edge. The local absence of salt is marked by a collapse of the overlying beds, and many other structural depressions not shown on the map are probably also related to the leaching of salt.

The Leofnard Member is mappable as a separate unit over the entire map area. In Saskatchewan, the member varies in thickness between 0 and 152.4 m (500 ft); in Alberta the maximum thickness is 207.3 m (680 ft).

Muskeg Formation. The anhydritic equivalents of the Prairie Evaporite and Dawson Bay formations in northern and central Alberta are known as the Muskeg Formation (see Fig. 23). The name was introduced by Law (1955) in northern Alberta for the light coloured succession of interbedded white and grey salt; brown anhydrite; brownish grey dolostone; and limestone which overlies the Keg River and underlies the Watt Mountain Formation. Law (1955, p. 1954) placed the top of the formation at the lowest occurrence of terrigenous clastics or at the base of limestone breccia. He selected the base of the formation at the facies change from evaporites to carbonates and selected as the type section the interval between depths of 1375.6 and 1588.0 m (4513 and 5210 ft) in the California Standard Steen River well, located in Lsd. 2, Sec. 22, Tw. 117, Rge. 5, west of the 6th meridian.

In this well, the contact between the evaporites and the underlying Keg River dolostone is fairly sharp and the upper contact coincides with the highest occurrence of dolostone below the Watt Mountain Formation. As originally defined, the Muskeg Formation of the type section includes three units. They are: a basal unit of interbedded anhydrite and dolostone, 158 m (521 ft) thick; a middle unit, 39.3 m (129 ft) thick, composed of dolostone; and an upper unit of interbedded limestone and dolostone, 14.3 m (47 ft) thick.

Regional correlations indicate that the two upper units increase in thickness to the northwest and grade into the upper part of the Pine Point Formation. The lower, evaporitic member increases in thickness to the southeast and gradually replaces the two upper non-evaporitic units. It grades into the interbedded salt and anhydrite facies of the Prairie Evaporitic Formation (see Fig. 53). The structural cross-sections (figs. 27, 31) in northern Alberta also indicate that the contact with the underlying Keg River Formation occurs at different stratigraphical levels and is not always sharply defined.

Law (1955) did not define the lateral boundaries between the Muskeg Formation and the Pine Point, Presqu'ile or Prairie Evaporite formations, and only mapped the interval between the top of the Keg River and the top of the Watt Mountain Formation (Law, 1955, Fig. 10). It is evident that the Muskeg Formation of Law (1955) is not homogeneous and is difficult to map. It is much easier to map the three units of the Muskeg Formation individually.

In an attempt to establish the boundary between the Muskeg Formation and the equivalent carbonates exposed in the Great Slave Lake area, Belyea and Norris (1962) redefined the upper contact of the Muskeg Formation. They correlated the upper part of the dolostone unit and the interbedded limestone and dolostone unit of the Muskeg Formation in the type section [together with the overlying limestone breccia in the lower part of the Watt Mountain Formation (Law, 1955)] with the Sulphur Point Formation of the Great Slave Lake region. The top of the redefined Muskeg Formation was selected at a depth of 1407.8 m (4619 ft), presumably the highest occurrence of evaporitic dolostone in the Muskeg Formation. Regional correlations indicate that the redefined contact is fairly sharp in places where the Muskeg Formation includes much anhydrite. In places where anhydrite is a minor constituent, the top of the redefined Muskeg Formation is difficult to select and the northern depositional limit of the redefined Muskeg Formation is equally difficult to map. In a later paper, Belyea did not map the Muskeg Formation separately, presumably because the boundary between evaporitic dolostones and non-evaporitic carbonates is difficult to establish (Belyea, 1971, Fig. 11).

The redefinition of the Muskeg Formation proposed by Belyea and Norris (1962) was accepted by some geologists (Hriskevich, 1966; Griffin, 1967). Others upheld the original definition of the Muskeg Formation (Grayston et al., 1964; McCamis and Griffith, 1967; Klingspor, 1969; Bebout and Maiklem, 1973). In this report, the term Muskeg Formation as redefined by Belyea and Norris (1962), is used for the interbedded anhydrite and dolostone facies. The interbedded anhydrite, shale, and carbonate facies, equivalent to the Dawson Bay and Prairie Evaporite formations mapped in Figure 52, is also considered as part of the Muskeg Formation.

The evaporitic deposits of the Muskeg Formation are widely distributed in northern Alberta, northeastern British Columbia, and in the southeastern part of the District of Mackenzie. The Muskeg evaporites attain a thickness of about 257.6 m (845 ft) in northeastern Alberta and a maximum thickness of 265.1 m (870 ft) in the area north of the Peace River Arch. Thick evaporitic sections occur in those areas where the interval between the base of the Watt Mountain and the top of the Keg River (or Winnipegosis) formations reaches its maximum thickness (see Fig. 52).

In northern Alberta, the Muskeg Formation occupies the entire interval between the top of the Keg River (or Winnipegosis) Formation and the base of the Watt Mountain Formation in a relatively narrow belt just northwest of the Peace River Valley. Northwest of this belt, the Muskeg Formation, as redefined by Belyea and Norris (1962), is overlain by the Sulphur Point Formation and includes much interbedded dolostone. The amount of dolostone interbeds increases to the west and northwest and, in places, it is difficult to select the upper and lower boundaries of the Muskeg Formation. The northwestern limit of the redefined Muskeg Formation coincides with the facies change from interbedded anhydrite and dolostone to non-evaporitic dolostone or interbedded dolostone and limestone. It is assumed that the absence of anhydrite interbeds indicates the limit of the evaporitic facies. Thus, the zero edge of the anhydrite shown in Figure 52 indicates the approximate limit of the Muskeg Formation.

Southeast of the Peace River Valley, the interbedded anhydrite and dolostone facies of the Muskeg Formation is gradually replaced by the salt and anhydrite facies of the Prairie Evaporite Formation (see Fig. 52). The boundary between the two formations was never defined and several authors have included the northwestern part of the salt and

anhydrite facies with the Muskeg Formation (Klingspor, 1969; Bebout and Maiklem, 1973; Corrigan, 1975). It is proposed that the boundary be defined above the highest occurrence of bedded salt.

The boundary between the Muskeg Formation and the equivalent of the Dawson Bay Formation in Alberta occurs in the area east of Fort McMurray. In Figure 53, the boundary is shown to occur east of the Algar River Q-13-87-17W4 well.

In central Alberta, the Muskeg Formation onlaps a paleotopographic high area, which includes the Peace River Arch and the Western Alberta Ridge. South and east of the Peace River Arch, the Muskeg Formation is represented by the "Shale and carbonate facies" shown in Figure 52. In that figure, the argillaceous beds equivalent to the upper part of the Winnipegosis Formation are mapped together with the salt-free equivalents of the Prairie Evaporite and Dawson Bay formations, and reach a thickness of a little more than 152.4 m (500 ft) north of Edmonton. These deposits thin to zero in a westerly direction because of depositional onlap. In the area just east of the zero edge, they directly overlie rocks of Precambrian or Cambrian age. North of the Peace River Arch, the "Shale and carbonate facies" is thin and unconformably overlies Precambrian granitic rocks.

In northeastern Alberta and in the southeastern part of the District of Mackenzie, the Muskeg Formation occurs at shallow depth or is poorly and discontinuously exposed southwest of Slave River. The evaporites were mapped together with the overlying evaporitic deposits of the Slave Point Formation by Norris (1965) as the Nyarling Formation, because the Watt Mountain Formation is thin or absent. The exposed parts of the Nyarling Formation consist mainly of gypsum and include minor interbeds of aphanitic limestone. Salt is presumably present locally because there are many saltwater springs near Salt River (Norris, 1963, p. 54). The thickness of the Nyarling Formation was estimated by Norris (1965) to be about 128 m (420 ft).

The structural cross-section of Figure 31 indicates that the geology of the Muskeg Formation in northern Alberta is complicated because of the local presence of carbonate mounds in the upper part of the Keg River Formation. Some of the carbonate mounds are reefal and porous, have a limited areal distribution, and extend to 213.4 m (700 ft) above the regional top of the Keg River Formation. These reefal mounds were described from the Rainbow Lake and Zama Lake area by Hriskevich (1966), McCamis and Griffith (1967), and Tranchant (1975). Other carbonate mounds equivalent to the lower part of the Muskeg Formation have a relatively large areal distribution and were mapped as part of carbonate shoals (see McCamis and Griffith, 1967, Fig. 8; Bebout and Maiklem, 1973, Fig. 31). These carbonates were not described but probably resemble the carbonate mud mounds of the Upper member of the Winnipegosis Formation, and may be bedded deposits of fossiliferous and pelletoidal carbonates. The interpretation in Figure 31 shows the reefal mounds as being sharply defined structures and the mud mounds having transitional boundaries.

The cross-section in Figure 31 also indicates that, in the Rainbow Lake area, salt is present between the reefal mounds. This salt bed is the Black Creek Member of the Muskeg Formation (Hriskevich, 1966). Other salt beds are locally present north of Zama Lake (McCamis and Griffith, 1967; Tranchant, 1975) and in the Hay River region. In Figure 52, the salt beds are shown as three separate deposits. Detailed correlations in the Muskeg Formation do not support the assumption that the salt bed north of Zama Lake is the same as the Black Creek Member (Tranchant, 1975), and Figure 31 does not suggest that the salt bed in the IOE

Henderson 5-18-113-22W5 well is connected with the Black Creek Member. However, earlier interpretations of the distribution given by McCamis and Griffith (1967, Fig. 9) Bebout and Maiklem (1973, figs. 34, 35), Davies and Ludlam (1973, Fig. 1), and Klose and Holland (1976, Fig. 1), suggest that all the salt beds in the lower part of the Muskeg Formation belonged, at least originally, to a single more or less continuous unit.

Hriskevich (1966), Tranchant (1975), and Klose and Holland (1976) discussed the relationship between the Keg River reef mounds, the salt beds, and the upper part of the Muskeg Formation. There is evidence that the anhydritic beds, which directly overlie the salt bed, onlap and overlap the reefal mounds; that the salt bed is absent around the base of the reefal mounds; and that the upper part of the Muskeg Formation is unusually thick in the area around the reefal mounds where the salt is absent. According to Bebout and Maiklem (1973), this situation suggests that some salt was leached around the reefal mounds during or just after the period in which the upper part of the Muskeg Formation accumulated. However, it is also possible that the reefal mounds are surrounded by anhydrite deposits, in the same way that the carbonate mound facies of the Upper member of the Winnipegosis Formation in Saskatchewan are surrounded by anhydrite (see Fig. 49).

The geology of the Muskeg Formation in the area straddling the boundary between Alberta and British Columbia west of Rainbow Lake is shown in Figure 31. Here, the Muskeg Formation includes relatively little anhydrite, because the facies boundary with the carbonate facies of the Pine Point Formation is near by (Morrow, 1973). In fact, the interpretation suggests that the CDR West Rainbow 12-10-109-12W6 well (Fig. 31) was drilled in the carbonate facies. In this area, the contrast between the carbonate mounds and the interbedded anhydrite and dolomite facies is difficult to map on seismic profiles.

Lithology. Little is known about the three salt members in the basal part of the Muskeg Formation. The Black Creek Salt was partially cored in the Banff Mobil Rainbow West well, located in Lsd. 9, Sec. 24, Tw. 109, Rge. 8, west of the 6th meridian, and locally contains chevron halite (Fuller and Porter, 1969a, Fig. 17). The salt is light grey, semi-translucent, coarsely crystalline, and contains thin stringers of anhydrite. The Black Creek salt member is 74.9 m (246 ft) thick in the Imperial Black Creek well, and is located in Lsd. 10, Sec. 27, Tw. 109, Rge. 9, west of the 6th meridian (see Hriskevich, 1969). The salt bed in the Zama Lake area is known only from one well, located in Lsd. 10, Sec. 21, Tw. 116, Rge. 5, west of the 6th meridian and is 37.8 m (124 ft) thick (Tranchant, 1975). The salt bed in the Hay River area was cored in the IOE Henderson well, located in Lsd. 5, Sec. 18, Tw. 113, Rge. 22, west of the 5th meridian and consists of clear, very coarsely crystalline halite with interbeds of anhydrite.

The salt beds are overlain by an interbedded succession of anhydrite and dolostone. The lower part of this succession onlaps or interfingers with the upper part of the carbonate mound facies (see Tranchant, 1975, Fig. 1). The upper part overlies the carbonate mounds and includes several markers. These markers have been used to correlate the sections in the Rainbow Lake area with the sections north of Zama Lake (Bebout and Maiklem, 1973; Tranchant, 1975).

The anhydritic beds that flank or interfinger with the carbonate mound facies in the Rainbow Lake area, consist of dark grey, interlaminated, very fine to fine grained limestone and anhydrite, grading upward to medium and dark grey,

Figure 54. Photographs of Upper Elk Point evaporites, core samples (true to scale, except e and f).

- a. Sharp contact between the Winnipegosis and Prairie Evaporite formations in the ARCO BA Poundmaker well, 12-38-45-22W3, Saskatchewan; depth 3609 feet (1100.0 m). Light brown, very finely grained and fine- to medium-peloidal dolomite grainstone, cemented by calcite or anhydrite and containing scattered, nodular inclusions of light grey or white, finely crystalline anhydrite (Winnipegosis Formation), is overlain by a thin bed of dark greyish brown, bituminous shale. This shale bed is in turn overlain by a greyish brown, contorted, nodular anhydrite bed composed of deformed, light coloured, laminated, anhydritic dolomite-mudstone fragments, peloidal wackestone fragments and a matrix of dark coloured, very finely crystalline anhydrite (Prairie Evaporite Formation, Shell Lake Member). The anhydrite matrix is in places recrystallized into dark nodules. The fragments may represent a sedimentary breccia.
- b. Nodular mosaic-anhydrite. Light grey, finely crystalline anhydrite nodules are separated from each other by very light brown, very finely peloidal, anhydritic dolomite and very dark, greyish brown, bituminous shale. The peloidal dolomite and bituminous shale may be regarded as the original sediment; the anhydrite nodules as a secondary, displacive deposit. Undifferentiated Shell Lake-Whitkow facies, Prairie Evaporite Formation; Chevron Hamilin Prov. well; 1-29-45-16W3; Saskatchewan; depth 3121.5 feet (951.4 m).
- c. Transitional contact between Winnipegosis and Prairie Evaporite formations in the ARCO BA Carruthers well; 10-11-45-23W3; Saskatchewan; depth 3794.5 feet (1156.6 m). The basal part of the sample represents the Winnipegosis Formation. It is a very light brown, very finely crystalline or finely peloidal dolomite-wackestone, partly cemented by anhydrite. It is overlain in the central part of the sample by an irregularly interbedded unit of dolostone and dark, bituminous shale. The dolostone beds are peloidal wackestones partly cemented by anhydrite. In the upper part of the sample, this lithology is partly anhydritized. The nodular-bedded anhydrite belongs to the Shell Lake Member of the Prairie Evaporite Formation.
- d. Greyish brown dolostone conglomerate, composed of peloidal-wackestone, mudstone, and fossil fragments cemented by dolomite, calcite and anhydrite. The vugs between the fragments are lined with a continuous, 0.2 mm thick layer of dolomite crystals and the remainder of the space is filled with semi-translucent calcite or anhydrite. In some vugs, white, nodular anhydrite has replaced the cement. Undifferentiated Shell Lake-Whitkow facies, Prairie Evaporite Formation; Chevron Hamilin Prov. well; depth 3032 feet (924.2 m).
- e. Thin section (magnification 2.5x) of a 10 cm thick, reddish and light brown mottled, finely to very coarsely peloidal dolomite-packstone. In the lower part of the thin section the peloids are cemented by halite. The halite is black in the figure because the photograph was taken with polarized light. Some peloids have an internal structure, others have a centre filled with halite. Anhydrite is present in the centres and along the periphery of the peloids in the form of scattered crystals. They form an irregular network of white lines in the photograph. Shell Lake Member, Prairie Evaporite Formation; Pheas. Banff Red Pheasant well; 13-19-40-15W3; Saskatchewan; depth 4128 feet (1258.2 m).
- f. Thin section (magnification 2.5x) of a greenish grey, silty shale bed with anhedral halite crystals. On the bedding surface of the core sample, the halite forms straight, V-shaped grooves. The photograph was taken with normal light and the halite is white. In the upper part of the sample, laminated, silty shale cuts off the salt crystals. The laminae in the area above the crystals are distorted, presumably because of local dissolution and collapse. Undifferentiated Shell Lake-Whitkow facies, Prairie Evaporite Formation; CP Keppel Forest well; 8-3-40-14W3; Saskatchewan; depth 4246.5 feet (1294.3 m).
- g. Sample contains a sharp contact, presumably representing a hiatus in deposition. Basal part is a light brown dolomite-mudstone, in places finely peloidal. The fine-peloidal parts are lighter coloured and are cemented by halite, the darker coloured areas are anhydritic and here the peloidal fabric is not apparent. Scattered, needle-like anhydrite crystals and several vertical anhydrite veinlets are present. In the centre of the sample the dolomite-mudstone is sharply overlain by a thin bed of dark greenish grey, anhydritic shale, which grades upward into a laminated, greenish grey anhydrite-mudstone. The anhydrite-mudstone includes light coloured lenses of finely peloidal dolostone, scattered dolomite mud clasts, and grey, irregular, finely crystalline anhydrite nodules. Undifferentiated Shell Lake-Whitkow facies, Prairie Evaporite Formation; Chevron Hamilin Prov. well; 1-29-45-16W3; Saskatchewan; depth 2991.5 feet (911.8 m).
- h. Core sample of uppermost bed of the Shell Lake Member in the Verbata no. 2 well, 7-24-41-24W3; Saskatchewan; depth 3894.5 feet (1187.0 m). Sample is a light brown dolomite-mudstone, in places very finely to finely peloidal, and cemented by halite. Dark layers include much brown bituminous material. Also present are scattered fenestral vugs filled with halite, and large, semi-translucent, subhedral to anhedral halite crystals containing fine clusters of pyrite.
- i. This core sample overlies the sample shown in h and is part of the lowermost unit of the Leofnard Member. It is composed of very coarse, semi-translucent, anhedral to subhedral halite crystals and irregularly shaped, greenish grey, argillaceous dolomite-mudstone fragments. The halite crystals are separated from each other by discontinuous dolomitic shale partings, and contain abundant, very fine, clusters of pyrite (?).

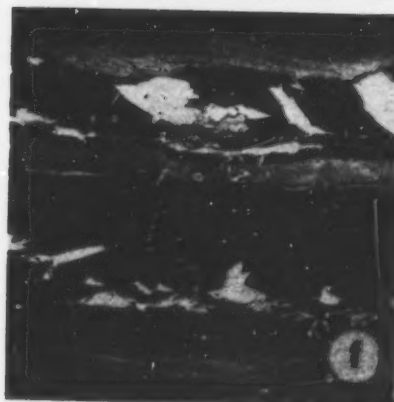
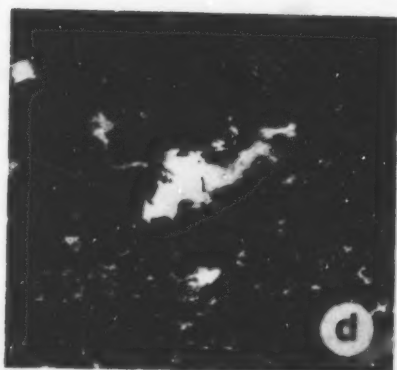


Figure 55. Photographs of Upper Elk Point evaporites. Core samples from the ARCO IOE Utikuma well, 4-2-83-9W5; Alberta (true to scale, except b, h and i).

- a. Succession of argillaceous and dolomitic beds; depth 5782 feet (1762.4 m). Unit A, Muskeg Formation, equivalent to Upper member, Winnipegosis Formation. Basal part of sample is a dark greyish green, silty claystone. It is overlain with a sharp contact by a very dark grey, laminated shale bed which contains, near the base, deformed mud clasts of the same lithology as the underlying claystone. The sharp contact may represent a hiatus in deposition. The laminated shale is dolomitic and contains green grains and granules, and layers with fine to medium quartz grains and pyrite crystals. A greyish brown and dark greyish brown, sandy dolostone overlies the dark shale with a transitional contact. The dolostone is a very fine to fine, peloidal packstone with scattered calcite or dolomite-filled charophyte oögonia (black dots on photograph); fine, waxy-green grains; and light brown dolomite mud clasts. The very dark grey bed near the top of the photograph is calcareous shale.
- b. Thin section of dolostone from sample a; depth 5781.5 feet (1762.2 m) (16.6x enlarged). Circular structure is an oögonium; smaller dark structures are peloids; and bright areas are composed of cellular material.
- c. Irregularly laminated and crosslaminated dolostone overlain by nodular-bedded anhydrite, Shell Lake equivalent; depth 5714 feet (1741.6 m). The dolostone is light brown, in part microcrystalline and porous, in part finely peloidal and cemented by halite or anhydrite. The dark grey, argillaceous interbeds outline several scoured surfaces. Scattered, black patches are anhydrite. The dolostone is sharply overlain by a thin, very dark grey, bituminous shale bed. This shale bed is in turn overlain by nodular-bedded anhydrite containing irregular lenses of light brown, peloidal dolostone, and discontinuous laminae of dark brown, bituminous shale.
- d. Light brown, microcrystalline dolostone with scattered anhydrite-filled casts of chevron-like halite crystals. Unit A, Muskeg Formation, Shell Lake equivalent; depth 5705 feet (1738.9 m).
- e. Greyish brown, microcrystalline dolostone overlies a thin, dark greyish green shale bed, and is sharply overlain by a very dark greenish grey, anhydritic shale. The dolostone is a peloidal wackestone that includes several scoured surfaces overlain by layers containing coarse mud clasts. These surfaces are locally distorted by small collapse structures (see arrows). In the centre of the sample are two quadrangular halite-crystal moulds filled with anhydrite. One of the moulds is partly filled with sediment and it is probable that the collapse structures have been caused by dissolution of former halite crystals. Unit A, Muskeg Formation, Shell Lake equivalent; depth 5736 feet (1748.3 m).
- f. Irregularly interbedded succession of light grey, mosaic anhydrite and very dark grey, massive anhydrite. The light coloured beds are parallel laminated and include triangular and quadrangular structures reminiscent of chevron halite. Each light coloured layer composed of anhydritized crystals is sharply overlain by a laminated mudstone. In the central part of the sample, the anhydritized layers are overlain by very dark brown anhydrite. In the upper part of the sample, the very dark brown beds are in turn overlain by olive-green shale. The shale contains white, anhydritic inclusions composed of microfossils (see figs. h, i). Unit B, Muskeg Formation; depth 5697 feet (1736.4 m).
- g. This sample overlies the sample shown in figure f. The lower part consists of olive-green shale and greenish grey, argillaceous anhydrite. It contains white inclusions of anhydritized microfossils. The anhydrite inclusions are also present in the upper part of the sample, which is a contorted-bedded, nodular-mosaic anhydrite. Unit B, Muskeg Formation; depth 5696.5 feet (1736.3 m).
- h, i. Thin sections of the anhydrite inclusions from figure g. Relatively well preserved microfossils (algal filaments and vascular plants?) are present. Enlargement of figure h is 105x; figure i, 42.6x.



Figure 56. The White Bear marker in the Vanscoy potash mine. Photographs a, b and f were taken in the tunnel at the base of the number one shaft in the Com'nco Vanscoy potash mine near Saskatoon, Saskatchewan.

- a. Bedded salt of the Prairie Evaporite Formation, about 10 feet (3.1 m) below the White Bear marker, in the wall of the "Decline", approximately 35 feet (10.7 m) above the bottom of the shaft. Photograph corresponds to interval 3715 to 3721 feet (1132.3-1134.2 m) in Figure 2 of Price and Ball (1973). Orange brown halite, interbedded with brown shale, is cut by vertical wedges of clear halite. The wedges are lined with red carnallitic halite and shale. In the ceiling of the "Decline" the wedges form a polygonal pattern similar to the pattern shown in Figure 57b.
- b. White Bear marker and overlying halite beds in the wall of the "Decline" at a height of about 45 feet (13.8 m) above the bottom of the number one shaft. Photograph corresponds to the interval between 3695 and 3707 feet (1126.2-1129.9 m) of Price and Ball (1973). The light coloured unit at the base of the photograph is a greyish green, argillaceous dolostone bed, varying in thickness between 40 and 70 cm. The basal contact of this bed is not present in the photograph but is highly irregular (see Fig. 2 in Price and Ball, 1973). The argillaceous dolostone grades upward through a thinly bedded unit (fig. c) into a light brown dolostone (fig. d). The argillaceous and thinly bedded units are cut by subvertical, reddish brown halite veins. The light brown dolostone includes very dark brown anhydrite nodules in domal structures. On the photograph, the dolomitic beds of the White Bear marker are overlain by very dark brown, nodular-bedded anhydrite. This unit of anhydrite is in lateral contact with a nodular-interbedded succession of semi-translucent halite and light grey anhydrite. The anhydrite unit thins to the left and is absent in the area farther away from the edge of the photograph, where the White Bear dolostone is overlain by halite. This situation suggests that the dark brown anhydrite has replaced the interbedded halite and anhydrite.
- c. Sample (true to scale) of the thinly interbedded, light brown and greenish grey, halite-impregnated dolomite-mudstone of figure b. One layer, with coarse grains, granules and pebbles of pale green, siliceous shale, is present. The bedding is offset by many fractures. Some fractures are filled with reddish brown halite (black on photograph). The halite in the fractures has locally spread sideways and has completely replaced some dolomitic beds.
- d. Two samples (true to scale) of the light brown, salt-impregnated dolostone of figure b. In the lower part, the dolostone includes brown, circular patches completely replaced by halite. Some of these patches grade into the reddish brown halite veins. The dolostone contains many dark brown, bituminous shale laminae, which are locally cut off by the domal, stromatolitic structures. In the upper part of figure d, the dolostone is sharply overlain by greyish brown anhydrite containing dark brown, wavy laminae of bituminous shale.
- e. Sample (true to scale) from the interbedded halite and anhydrite unit that overlies the White Bear marker in the Vanscoy mine. It includes semi-translucent halite and thin, undulating beds of light grey, dolomitic anhydrite. The original sedimentary structures in the anhydritic beds are poorly preserved.
- f. View of the ceiling of the "Decline", showing the underside of one of the many undulating anhydrite interbeds of the succession directly overlying the White Bear marker. The undulations show a pattern reminiscent of a rippled surface.

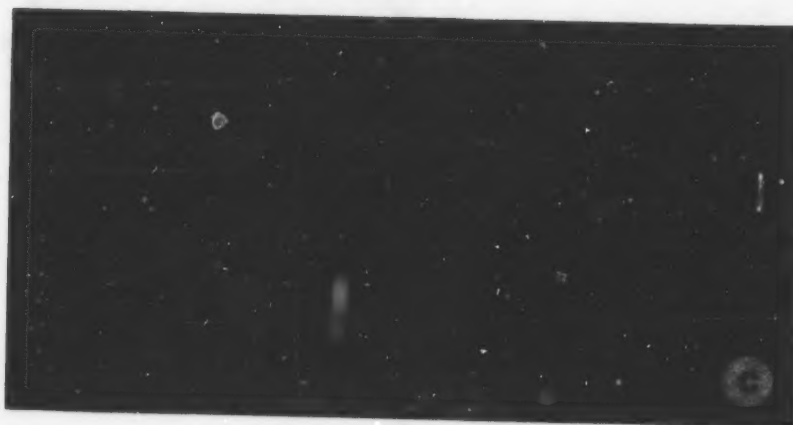
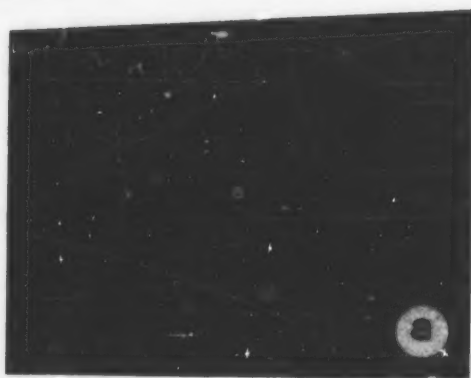
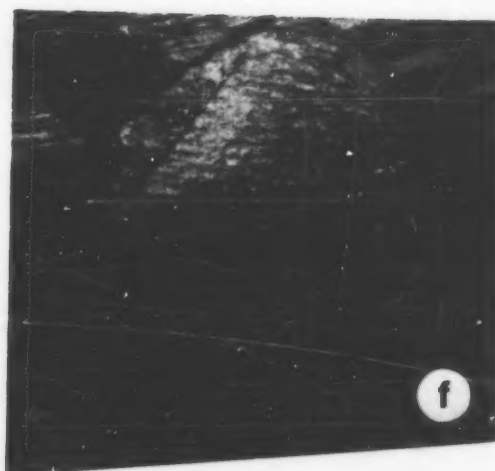
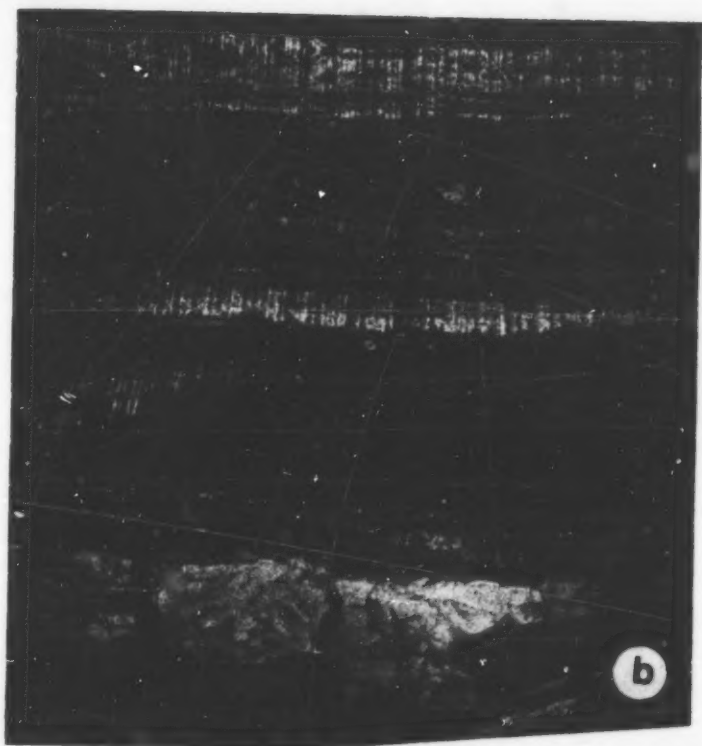


Figure 57. Photographs of Upper Elk Point evaporites, potash beds. Photographs b and c were taken in the Cominco Vanscoy potash mine, near Saskatoon. The other photographs are from core samples.

- a. Core sample (true to scale) of yellowish brown, semi-translucent halite. The basal part and the left side of the sample are indistinctly bedded and consist of a mosaic of crystals that are fairly uniform in size (0.5-1 cm). Individual beds are separated by thin, greenish grey shale partings. The right side of the sample consists of very large, light grey, semi-translucent halite crystals separated by dark reddish brown, anhedral, sylvite crystals (black in photograph). The contact between the two lithologies is vertical (see arrows). Upper part Leofnard Member, Prairie Evaporite Formation; Husky HD Wildmere well; 10-3-49-6W4; Alberta; depth 3818 feet (1163.7 m).
- b. Polygonal fractures filled with large sylvite crystals and reddish brown shale. Ceiling of "Decline" tunnel; Belle Plain potash beds; Vanscoy mine. The polygons are about 1 m across. In the walls of the tunnel the fractures extend downwards as subvertical veins similar to the one shown in photograph a.
- c. Syneresis cracks in a reddish brown, mottled dolomitic shale interbed just below the Belle Plain potash beds. Ceiling of "Decline" tunnel, Vanscoy mine.
- d. Core sample (true to scale) of potash ore; upper part Leofnard Member; BA Cutknife Rutley well; 12-14-43-22W3; Saskatchewan; depth 3471 feet (1058.0 m). Lower right part of sample consists of subhedral, light coloured, semi-translucent sylvite (white arrow) and halite (partly covered by letter d) crystals surrounded by dark reddish brown, anhedral sylvite. Upper part of sample is a mosaic of light coloured, semi-translucent halite and sylvite, very dark coloured red-brown sylvite, and light greenish grey, siliceous shale (white on photograph).
- e. Core sample (true to scale) of potash salt; upper part Leofnard Member; Pet. Cal. Dina well; 10-32-45-1W4; Alberta; depth 3470 feet (1057.7 m). Lower part of sample is a mosaic of light coloured, semi-translucent halite and dark coloured, reddish brown sylvite. The subhedral halite and anhedral sylvite crystals are separated by greenish grey shale partings (white on photograph). The upper part of the sample is a greenish grey, dolomitic shale bed cut by reddish brown sylvite veins. Some sylvite veins extend downward into the salt bed below. On the bedding surface at the top of the sample the fractures form a polygonal pattern.
- f. Core sample (true to scale) of reddish brown halite facies; uppermost Leofnard Member; BA Cutknife Rutley well; depth 3449 feet (1051.3 m). Rusty brown and semi-translucent halite crystals are separated from each other by partings and irregular interbeds of reddish brown, siliceous shale (light grey on photograph). The shale appears to have been displaced by the halite crystals (compare with Fig. 15a).
- g. Contact (marked by white arrow) between Prairie Evaporite salt (below) and reddish brown claystone of the Dawson Bay Formation (above). The halite is rusty brown coloured and semi-translucent. The reddish brown claystone in the upper part of the sample is interbedded (nodular relationship) with greenish grey claystones. The lower part of the claystone is brecciated and contains salt-filled vugs (black on photograph). The breccia fragments are angular and may represent former halite crystals.

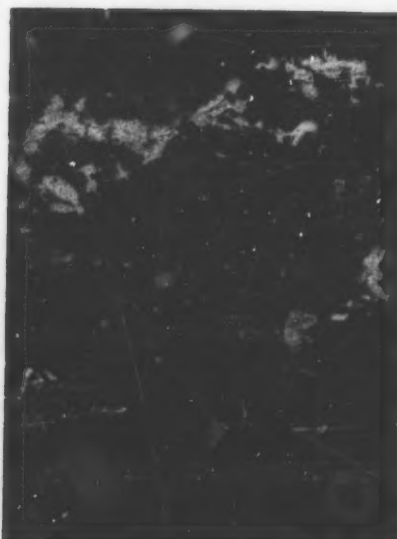
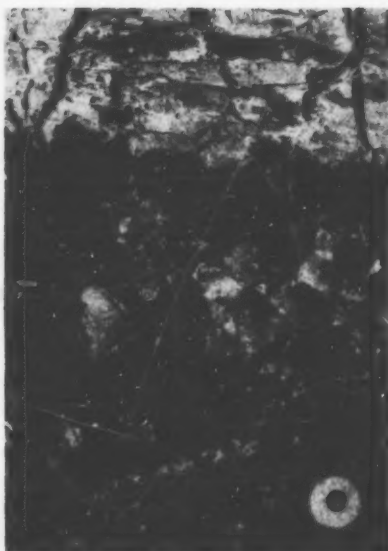
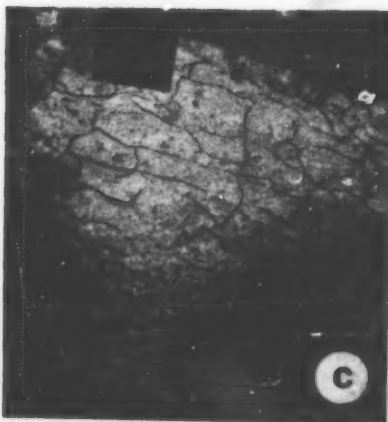
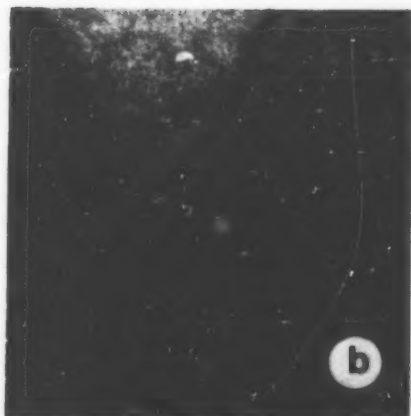


Figure 58. Photographs of Upper Elk Point evaporites. Core samples from the basal part of the Leofnard Member, Prairie Evaporite Formation; Pan Am Chipewyan well; 10-16-91-18W4; Alberta (true to scale, except c).

- a. Very coarsely crystalline, semi-translucent halite (dark grey and white on photograph) overlain by a discontinuously laminated mixture of light brown, anhydritic dolostone and greenish grey, argillaceous dolostone. The dark, anhedral halite crystals on the lower left side of the sample contain nodular inclusions of dolomite-mudstone; the subhedral halite crystals on the lower right include isolated fragments of mudstone (arrow), and scattered, very fine to fine clusters of pyrite crystals. It appears that the halite crystals have displaced the dolomite-mudstone. Depth 2751 feet (838.5 m).
- b. Very coarse grained floatstone overlain by thinly interbedded mudstone and halite. The floatstone consists of light brown, microcrystalline, dolomitic matrix; brown "grains" of halite, and grey, nodular, anhydritic mudstone-pebbles. The halite "grains" are described in figure c. The mudstone-pebbles include irregular vugs filled with halite. The floatstone is sharply overlain by grey, dolomitic anhydrite-mudstone and semi-translucent, impure halite beds. The halite beds include brown inclusions similar to the "grains" of figure c.
- c. Thin section of the "grains" from sample b (magnification 16.6x). The "grains" are poorly preserved microfossils (ostracodes?) or fragments of organic structures (pisoliths or oögonia), which are partly replaced by halite and also surrounded by a white halo of halite.
- d. Example of one of the anhydritic dolostone beds which occur as interbeds in the Leofnard Salt. Depth 2728 feet (831.5 m). The sample is composed of a mixture of light brown dolomite, greyish brown anhydrite and semi-translucent halite. It includes light coloured, parallel laminated dolomite-mudstones cemented by anhydrite; light coloured, wavy or contorted, very fine grained or peloidal dolomite-wackestones with scattered dark-coloured anhydrite-mudstone pebbles, deformed nodular inclusions of anhydrite, and fine shreds of bituminous material; and greyish brown anhydrite-mudstones which include many small, elongate anhydrite nodules, discontinuous layers of secondary anhydrite and fenestral vugs filled with halite. The boundaries between the light and dark coloured beds are scoured surfaces, and some of the beds were deformed before a new layer of sediment was deposited. This suggests that deposition was not a continuous process. The uppermost and lowermost beds in the sample are delicately laminated. They include dark brown, bituminous laminae and many fenestral vugs filled with halite. These beds are transitional to the impure halite beds which underlie and overlie the beds shown in the sample.
- e. Interbedded halite and anhydrite-mudstone. Boundaries between beds are indicated by black markers. The irregularly laminated, greyish brown bed in the lower part of the sample overlies a colourless, semi-translucent halite. It consists of light coloured dolomitic, and dark coloured anhydritic mudstone layers cemented by halite, and includes fenestral vugs filled with subhedral or anhedral halite (arrow). The amount of halite increases toward the top of the bed. Above the lower set of black markers is a succession of three halite beds (see markers). The lower bed is light brown and contains much disseminated anhydritic mud. The light coloured halite bed in the middle is semi-translucent and pure. The upper halite bed is also pure but includes, near the top, an area marked at the base by a deformed anhydritic layer (arrow). This area contains triangular and quadrangular structures (arrow) composed of anhydritic halite. The structures are reminiscent of chevron-halite. The mass of chevron-halite seems to have displaced the upper contact (upper set of markers) in an upward direction. The uppermost part of the sample includes three greyish brown, anhydrite-mudstone layers cemented by halite. The middle layer includes a large subhedral halite crystal (upper left). The upper layer is laminated.

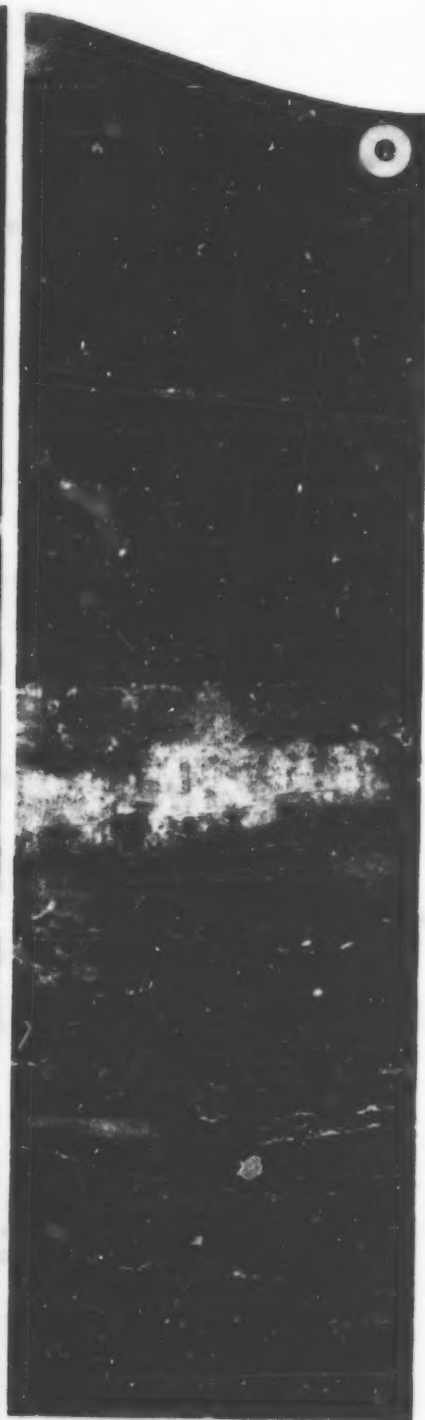
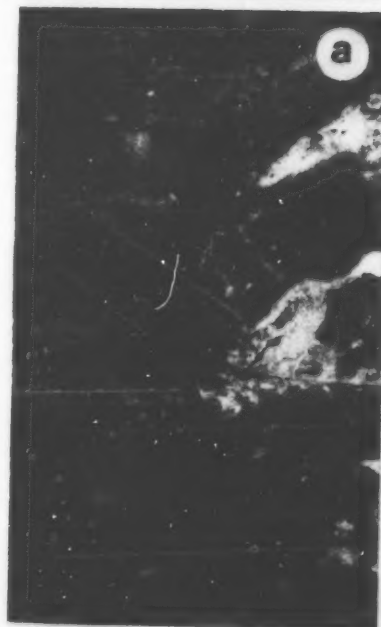
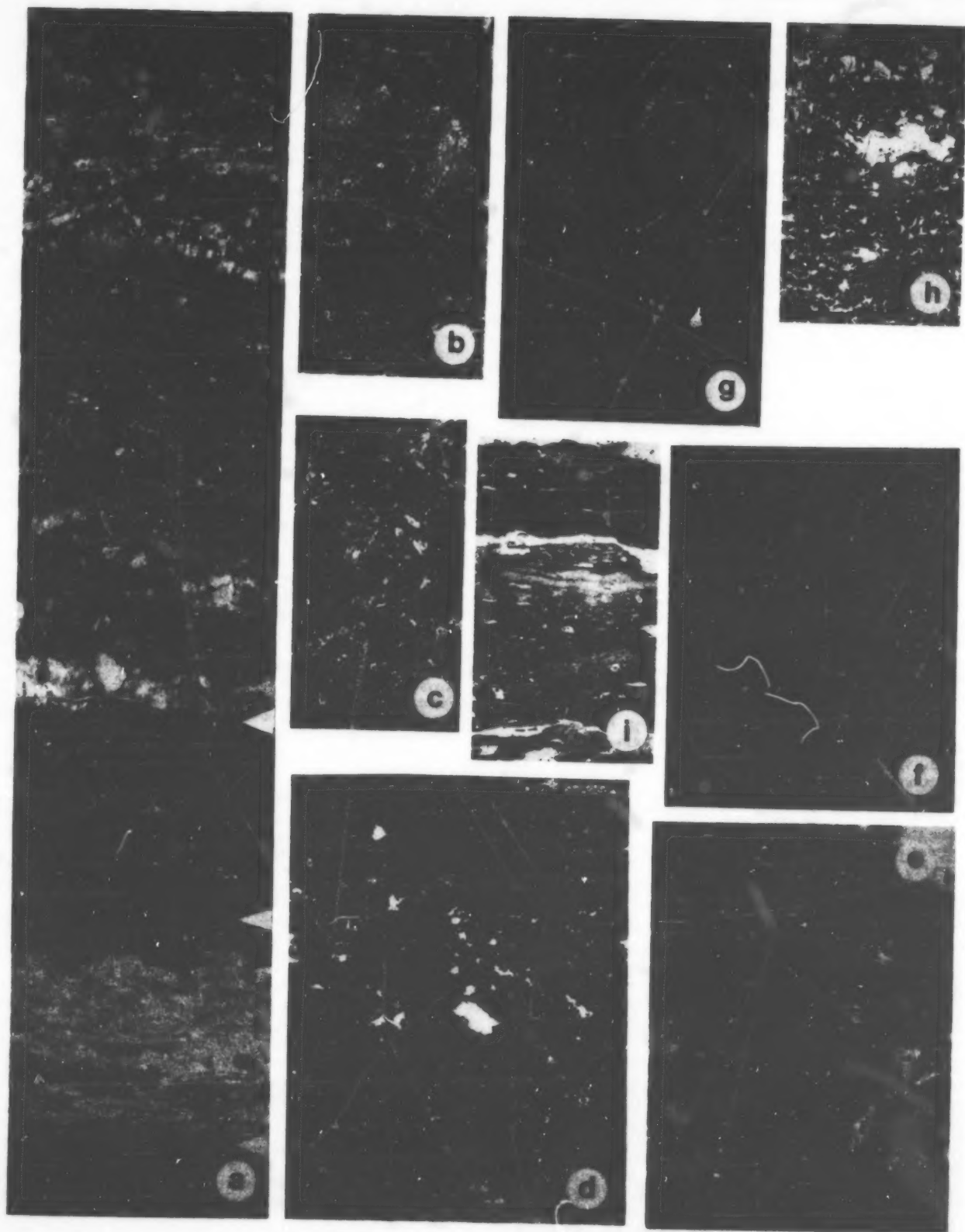


Figure 59. Photographs of Upper Elk Point evaporites, nearshore facies (true to scale, except b, c, d, h and i).

- a. Core sample of an interbedded succession of dolostone, anhydrite and halite; Leofnard Member; BA Bat Lake well; 6-31-84-7W5; Alberta; depth 5071.5 m (1545.8 m). Lithology is discussed from the base upward; bed boundaries are marked by white triangles. Lowermost bed is dark greenish grey, anhydritic shale. It grades upward into a greyish brown, peloidal, anhydritic dolomite-wackestone with many, discontinuous, argillaceous laminae, small compressed anhydrite nodules, and scattered, halite-filled, fenestral vugs. This bed is light grey on the photograph. Near the top of the light coloured wackestone all the anhydrite inclusions are flattened by compaction. The contact with the overlying, very dark brown anhydrite-mudstone is fairly sharp. The mudstone bed includes a very dark layer at the base, a lighter coloured, coarsely peloidal layer cemented by halite in the middle, and a greyish brown coloured layer at the top. The upper half of the sample is an irregularly bedded unit composed of light brown, very coarse peloids and peloidal layers of anhydritic dolomite; scattered, very dark grey, bituminous layers; and a cement of semi-translucent, colourless halite (see figs. b and c).
- b, c. Thin sections of the very coarse peloidal bed in the upper part of figure a. The photograph was taken with polarized light and halite is black. The grey areas are dolomite, the very light areas are anhydrite. The peloids are mainly dolomite; they are surrounded by a coating composed of radially arranged anhydrite crystals. Magnification of b is 2.5x; c is 16.6x.
- d. Thin section (enlargement 16.6x) of an anhydritic dolomite-wackestone similar to the peloidal wackestone in the lower part of figure a. BA Bat Lake well; Leofnard Member; depth 5062 feet (1542.9 m). In this sample, the peloidal fabric is well preserved. The wackestone consists of fine to coarse peloids of dolomite surrounded by an argillaceous, dolomitic matrix. The best preserved peloids are in the central part of the thin section where the matrix is locally absent. Some of the peloids have an anhydritic centre, others are partly filled with halite, and in some instances the peloids are surrounded by anhydrite or halite. In the basal part of the thin section the rock is largely anhydritized and the peloidal fabric is not apparent. In the upper part of the thin section the peloids form coarse to very coarse nodular structures partly replaced by anhydrite or halite (see Fig. 61c). The thin section also contains fenestral vugs filled with halite (white on photograph) and a laminated mud clast (right edge, just above centre).
- e. Chevron halite mixed with anhydrite-mudstone. Halite is underlain by anhydrite-mudstone cemented by halite and is sharply overlain by a parallel laminated, anhydritic, dolomite-mudstone. The dolomite-mudstone grades upward into a thin, dark unit consisting of bituminous laminae separated by mudstone. Leofnard Member; BA Bat Lake well; depth 5074 feet (1546.6 m).
- f. Nodular-bedded, light and dark brown banded anhydrite with irregular, bituminous shale partings. In the upper part of the sample the original laminated fabric is locally preserved in a lens of light greyish brown anhydrite-mudstone. Unit B, Muskeg Formation; ARCO IOE Utikuma well; 4-2-83-9W5; Alberta; depth 5695.5 feet (1736.0 m).
- g. Greyish brown, coarsely peloidal, anhydritic dolomite-packstone with dark brown, bituminous shale laminae. The packstone is similar to the peloidal beds in the upper part of figure a and is partly cemented by semi-translucent halite. The irregular, bituminous laminae locally include subhedral halite crystals (arrows). The halite crystals have displaced the bituminous shale laminae. Leofnard Member; BA Bat Lake; depth 5060 feet (1542.3 m).
- h. Thin section of sample g (magnification 2.5x). Photograph taken with normal light. Grey, peloidal beds and black bituminous laminae are locally displaced by subhedral halite crystals (compare with fig. 18f).
- i. Thin section (magnification 2.5x) of a greenish grey, anhydritic shale containing discontinuous layers and burrow-like inclusions of dolomite. The dolomite is locally replaced by anhydrite. Muskeg Formation, Shell Lake equivalent; ARCO IOE Utikuma well; depth 5705 feet (1738.9 m).



bedded anhydrite, intercalated with dark coloured, laminated dolostone containing calcispheres. This interval includes brecciated anhydrite. Bebout and Maiklem (1973, Fig. 20) assumed that the breccia represents a leached interval formerly occupied by as much as 82.3 m (270 ft) of salt. In the area north of Zama Lake, the beds flanking the carbonate mounds consist of nodular-mosaic and mosaic anhydrite with a few interbeds of dolostone (McCamis and Griffith, 1967).

The succession that overlies the carbonate mounds includes several units composed of dolostone. In the area north of Zama Lake, the "Zama Member" of McCamis and Griffith directly overlies the reefal mounds and consists of brown, laminated, and discontinuously laminated, fine to medium recrystallized dolostone with rare brachiopods and *Amphipora*-like fossils. In the Rainbow Lake area, the "Rainbow Dolostone Member" of Bebout and Maiklem consists of medium to dark brown, laminated and burrowed dolostone, which includes a fossiliferous bed containing *Amphipora* and brachiopods. In both areas, the intervening evaporites include many dolostone to anhydrite cycles (Bebout and Maiklem, 1973). Each cycle starts at the base with a medium-dark brown, laminated or burrowed dolostone, in places containing calcispheres. The laminated dolostone grades upward into dolostone with irregular, dark grey laminae of bituminous shale, and angular anhydrite nodules. The irregularly laminated dolostone is overlain by dolostone with abundant nodular and nodular-mosaic anhydrite, which grades upward into massive-mosaic anhydrite. The complete cycle contains, at the top, a dark unit of bedded, massive anhydrite. Many cycles are incomplete and units are missing either because of nondeposition or erosion (see Bebout and Maiklem, 1973, Fig. 25).

The few published lithologic descriptions of the Muskeg Formation outside the Rainbow and north Zama Lake areas suggest that the dolostone and anhydrite cycles are widely distributed in the upper part of the Muskeg Formation. They probably correlate with the anhydrite to halite cycles present in the upper part of the Prairie Evaporite Formation in northeastern Alberta (Bebout and Maiklem, 1973).

The upper contact of the Muskeg Formation, as redefined by Belyea and Norris (1962), is a facies change which steps downsection in a westerly to northwesterly direction. The lower contact is also a facies change, and a cross-section in the area north of Bistcho Lake (Fig. 60) suggests that both the upper and lower contacts represent the same facies change. The evaporitic beds of the Muskeg Formation, as redefined by Belyea and Norris (1962), grade upwards and northwestwards into a well bedded and locally laminated succession of brown and light brown, very fine to finely crystalline, in part porous, dolostone containing scattered, poorly preserved peloidal beds, cryptalgal laminites and *Amphipora*-like fossils. The facies change coincides with the northern zero edge of the anhydrite shown in Figure 52. The dolostone beds grade in turn into a succession of interbedded brown, micritic, argillaceous limestone and brown, in part porous, fine to medium peloidal limestone, with scattered *Amphipora*-like fossils, gastropods, ostracodes and cryptalgal laminae. This facies change is not indicated in Figure 52.

The nearshore "Shale and carbonate facies" of the Muskeg Formation south of the Peace River Arch was studied in some detail by the writer. The lower part of this succession was cored in ARCO IOE Utikuma 4-2-83-9-W5 well (see Fig. 53) and was described earlier with the Shell Lake and Leonard members. Unit A of Figure 53 is a succession of interbedded, greenish grey, anhydritic shale, light brown dolostone, and light grey or grey nodular-bedded anhydrite. The dolostone beds are anhydritic, laminated or

bioturbated and commonly contain halite crystal moulds (see Fig. 55c, d, e). The shale beds overlie the dolomitic beds with a sharp contact (Fig. 55e). They are parallel laminated and grade upward into indistinctly laminated, bioturbated, dolomitic shale in a similar fashion to that shown in Figure 55a. An example of a bioturbated, dolomitic, and anhydritic shale is shown in Figure 59i. Some dolostone beds are sharply overlain by nodular-bedded anhydrite (Fig. 55c). The argillaceous equivalents of the Shell Lake Member (see Fig. 53), described above as Unit A, are overlain by an anhydritic unit composed of light coloured, dolomitic anhydrite, dark grey, argillaceous anhydrite, and greenish grey shale (Unit B in Fig. 53). Only the lower part of Unit B was cored in the Utikuma well. Typical examples of this lithology are shown in figures 55f, g, h, i and 59f. They include beds with abundant microfossils (algae?), anhydritized relicts of chevron halite, and bituminous layers reminiscent of algal mats. The upper part of the nearshore facies of the Muskeg Formation and the overlying beds of the Watt Mountain Formation were cored in the Shell IOE Driftwood well, located in Lsd. 10, Sec. 12, Tw. 73, Rge. 3, west of the 5th meridian. In this well, the lower part of the core represents the upper part of Unit B in the Utikuma well (see Fig. 53). It is an interbedded unit of greenish grey shale, dark grey argillaceous anhydrite, and light brown, dolomitic anhydrite. The dolomitic beds are bioturbated or parallel laminated (see Fig. 61e) and commonly contain halite crystals or halite cement. They are sharply overlain by the dark coloured argillaceous beds. Some light coloured, dolomitic beds are completely replaced by nodular anhydrite (Fig. 61f). In the upper part of Unit B, the greenish grey argillaceous beds contain irregular, red-brown mottles (Fig. 61d).

The interbedded succession of Unit B is capped by a massive, greyish green and reddish brown mottled breccia, composed of large, unsorted, light grey, light green or dark green, deformed fragments of dolostone or anhydrite and red-brown shale (Unit C). Unit C forms a prominent, 3 m (10 ft) thick bed at the top of the Muskeg Formation and is sharply overlain by a greyish green and red-brown mottled, dolomitic claystone, which forms the basal unit of the Watt Mountain Formation (see Fig. 60b). The upper part of the reddish brown anhydrite breccia was cored in a number of other wells (see Jansa and Fischbuch, 1974).

Evaporitic deposits of the Dawson Bay Formation. The Dawson Bay Formation was defined as a map unit in the Paleozoic outcrop area of southwestern Manitoba by Baillie (1951), and was later recognized in the subsurface of Saskatchewan (Baillie, 1953). In the region of Lake Winnipegosis, the formation overlies the Winnipegosis Formation with a sharp contact. In the subsurface, it overlies the Prairie Evaporite Formation. The upper contact is defined at the base of a reddish brown and green mottled shale unit that forms the basal unit of the Souris River Formation.

The formation in the subsurface includes a lower redbed member, a middle carbonate member, and an upper member named the Hubbard Evaporite (Lane, 1959). The formation is widely distributed in southwestern Manitoba, southern Saskatchewan, and east-central Alberta, where it overlies the Prairie Evaporite Formation. It is more than 67 m (220 ft) thick in the subsurface northeast of Regina, where it includes an upper unit of salt. The formation thins in all directions away from this depocentre. In Alberta, the formation becomes increasingly anhydritic and in central and north-eastern Alberta it merges with the lower part of the Watt Mountain Formation and upper part of the Muskeg Formation (see Fig. 53).

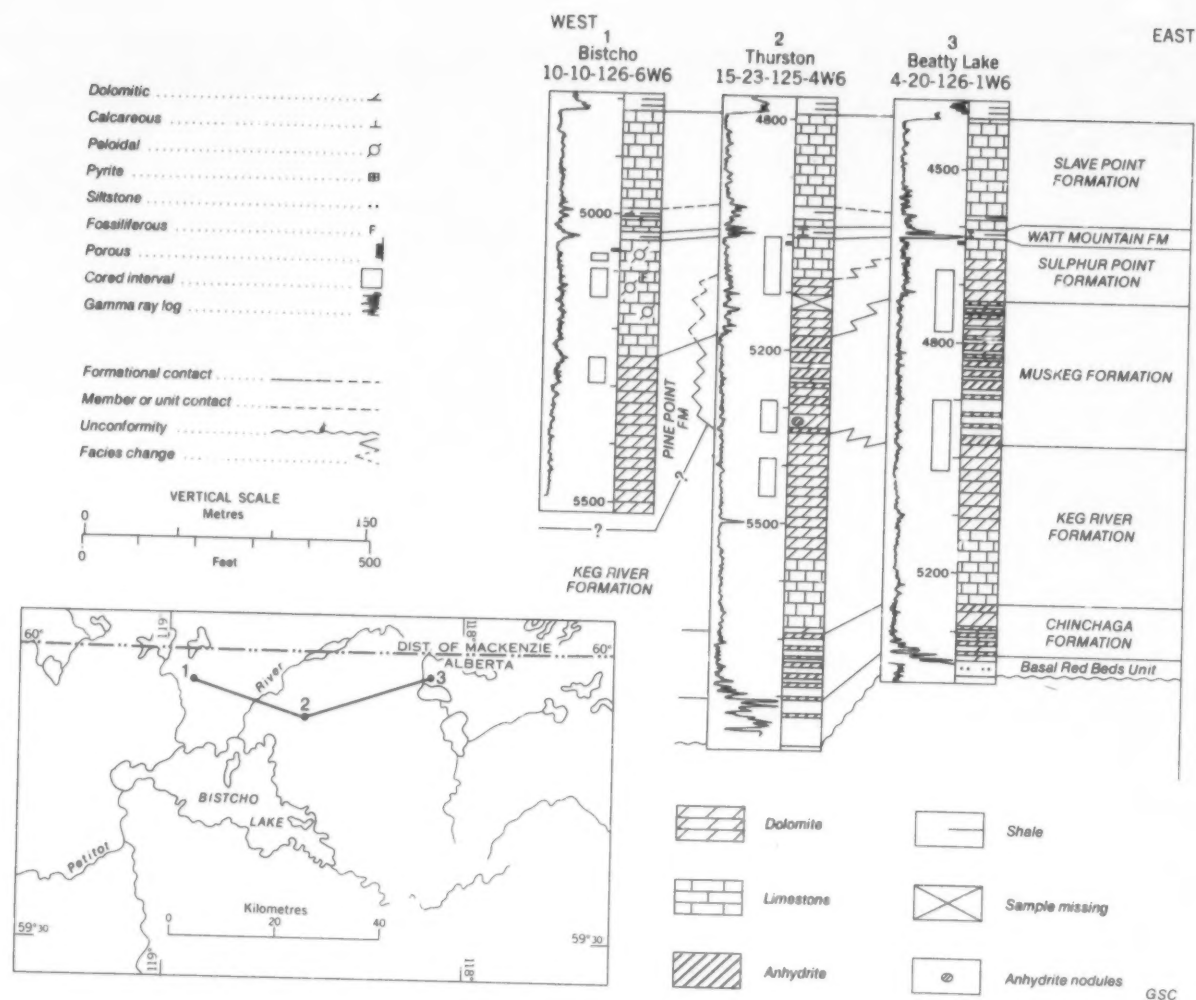


Figure 60. Stratigraphic cross-section, Elk Point Group, Bistcho Lake, northern Alberta.

The lower redbed member or "Second Red Bed" varies in thickness between 3 and 12.2 m (10 and 40 ft) and includes three units. A basal unit of reddish brown, in places green mottled, dolomitic shale; a greenish grey dolomitic claystone; and an upper interbedded unit of greenish grey, argillaceous dolostone, dolomitic claystone, or calcareous mudstone. In places where the basal unit directly overlies the Prairie Evaporite Salt it contains inclusions, crystals, and veinlets of pink halite and, in Alberta, thin, irregular beds of anhydrite. Only the basal unit is evaporitic; the two other units of the lower redbed member do not include evaporitic minerals and the upper unit is locally fossiliferous (Price and Ball, 1971; Dunn, 1982).

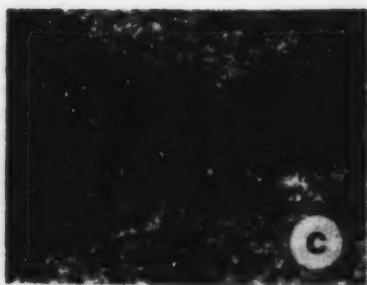
In places where the Prairie Evaporite Salt is partly leached from the subsurface, the basal unit is brecciated and contains veins of halite and anhydrite. Here, the insoluble, argillaceous beds in the upper part of the Prairie Evaporite Formation have accumulated below the redbeds and are inseparable from the lower redbed member. In places where the salt of the Prairie Evaporite Formation is completely dissolved, the lower redbed member is thus generally thicker than in the area where the salt section is complete.

In the central part of southern Saskatchewan, the lower redbed member is overlain by a micritic limestone which grades upward into fossiliferous limestone (Lane, 1959; Dunn, 1982). The limestone is locally porous but in many wells the original intrafossil porosity is filled with halite (see Price and Ball, 1971, 1973). Overlying the limestone is a succession of microgranular limestone, fossiliferous limestone, pelletal limestone, and dolomitic limestone, which usually includes 30 to 60 per cent secondary halite. The interbedded fossiliferous unit is overlain by interbedded microcrystalline dolostone and dolomitic anhydrite.

The salt member was named the Hubbard Evaporite by Lane (1959). The areal distribution and thickness of the Hubbard Evaporite are shown in Figure 62, which is redrawn from Lane's figure. The thickness of the salt varies between 0 and 18.9 m (0 and 62 ft) and the zero edge of the salt is depositional, except in the northeast where the edge is due to dissolution (Lane, 1959, p. 29). The Hubbard Evaporite Member consists of colourless to amber, semi-translucent, coarsely crystalline halite. It contains minor inclusions and interbeds of green and red dolomitic shale and thin partings of dolostone and anhydrite (Lane, 1959). Scattered fragments

Figure 61. Photographs of Upper Elk Point evaporites. Core samples of the redbed and nearshore facies, Muskeg and Prairie Evaporite formations (true scale, except c).

- a. Sediment-filled fractures in thinly bedded anhydrite-mudstone. The mudstone includes greenish grey anhydrite beds; light brown, indistinct peloidal, dolomitic anhydrite beds; and discontinuous layers of rusty brown, chevron halite. The fractures in the lower part of the sample are filled with a poorly bedded mixture of anhydrite-mudstone and halite. The light coloured mass of halite crystals in the central part of the sample fills the upper part of a fracture or collapse structure. In the upper part of the sample the beds are brecciated and the fractures are filled with dark grey, argillaceous anhydrite. The breccia is sharply overlain by dark grey, anhydritic shale. This sharp contact may represent a hiatus in deposition during which the underlying beds were desiccated. BA Bat Lake well; 6-31-84-7W5; Alberta; depth 5063.5 feet (1543.4 m).
- b. Pseudobreccia grading upward into pale coloured claystone. This change in lithology represents the boundary between the Muskeg (below) and Watt Mountain formations (above). Shell IOE Driftwood well; 10-12-73-3W5; Alberta; depth 5054.5 feet (1540.6 m). The pseudobreccia is composed of irregular, reddish brown anhydrite nodules and a green and maroon mottled, anhydrite-wackestone matrix. Arrow points to two mud pebbles which are cut by a red-brown band. The upper part of the sample is a light greyish green, dolomitic claystone which includes small, light coloured anhydrite nodules and anhydritic patches. These patches have a peloidal texture. Similar nodules and light coloured patches are present in the wackestone matrix of the pseudobreccia. There is no discontinuity between the pseudobreccia and the claystone; the formation boundary coincides with the upper limit of the reddish brown nodules.
- c. Detail of thin section in Figure 59d under polarized light (magnification 16.6x) showing microcrystalline mixture of anhydrite (white), dolomite (grey, dark grey) and halite (black). The curved, tubular structures may represent algal filaments; the nodular mass of dark, intertwined tubes, partly cemented by halite, may represent faecal pellets.
- d. Redbed facies; Unit C, Muskeg Formation, Shell IOE Driftwood well; depth 5064 feet (1543.5 m). Sample includes four beds. Lowermost bed is a dolomitic anhydrite-mudstone, greyish brown with red-brown (dark) and pale green (light) mottles. The small, horizontally arranged mottles in the basal part of the sample surround a fine, black mineral deposit. The mottled mudstone is overlain by a thin, light coloured, dolomitic mudstone bed which contains many small nodules of secondary anhydrite and locally has a finely peloidal fabric. The light coloured bed is overlain by a greenish grey, reddish brown mottled, argillaceous and anhydritic mudstone. This mudstone also includes small, deformed anhydrite nodules. The reddish brown mottles, the green colour and the argillaceous content fade away in an upward direction and, in the upper part, the mudstone is light brown, dolomitic and locally very finely peloidal. Scattered fine to coarse, fenestral vugs filled with anhydrite are present. The dolomite-mudstone is sharply overlain by a green, anhydritic shale with many compressed, anhydrite filled, fenestral vugs. Near the top of the sample the vugs are filled with reddish brown anhydrite.
- e. Nearshore facies, Unit B Muskeg Formation; Shell IOE Driftwood well; depth 5090 feet (1551.4 m). Interbedded succession of light greyish brown dolomitic-packstone; dark grey, argillaceous anhydrite-mudstone; light brown, dolomitic-mudstone; and very dark grey, anhydritic shale. The dolomite packstone in the lower part of the sample consists of very fine to fine peloids and nodular masses of tubular pellets similar to those shown in figure c. The matrix of the packstone is argillaceous and silty. Both the matrix and the particles are extensively anhydritized. The light coloured, parallel-laminated mudstone in the upper part of the sample is very fine grained and cemented by anhydrite. It is erosionally overlain by a very dark, anhydritic shale, containing many deformed, dolomitic mud pebbles and small anhydrite nodules.
- f. Redbed facies, Unit C Muskeg Formation; Shell IOE Driftwood well; depth 5070 feet (1545.3 m). A pale brown, very anhydritic, dolomite-mudstone is overlain by nodular-bedded anhydrite. In the basal part of the sample the mudstone includes two thin, locally reddish brown mottled layers containing deformed, fine to coarse particles. These layers are cut by a small fault, along which sediment has moved upward into the overlying beds. The upper part of the mudstone bed is delicately crosslaminated and the laminae are offset by small growth faults. In the nodular-bedded anhydrite the original sedimentary structures are not preserved, but the brown, dolomitic shale partings indicate the bedding (compare with Fig. 59f).



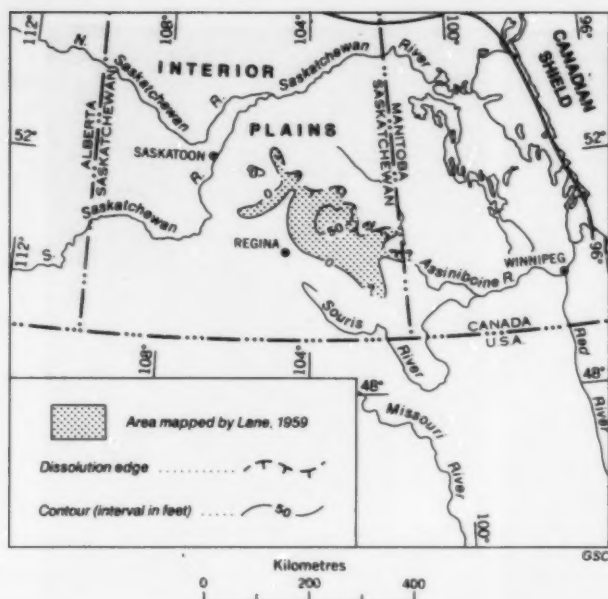


Figure 62. Isopach map, Hubbard Evaporite, Dawson Bay Formation, southern Saskatchewan.

of insoluble rocks are present in the salt along the northern edge of the member and indicate that dissolution and brecciation has taken place (Lane, *ibid.*). The salt unit was cored completely in the Winsal Beaverdale well, located in Lsd. 3, Sec. 32, Tw. 26, Rge. 7, west of the 2nd meridian. Only the lower part of the member has been cored in other wells (see Lane, 1959, Appendix II).

The succession of interbedded carbonates and anhydrite which underlies the Hubbard Evaporite was described by Lane (1959) as the DB-5 member. This is apparently not a useful subsurface map unit because the lower contact with the fossiliferous limestone is not recognizable on borehole logs. On the electric logs (in the absence of density logs) it is also impossible to separate the dolomitic anhydrite interbeds from the fossiliferous limestone beds containing secondary anhydrite and halite. The DB-5 member can thus only be recognized in cores, where it varies in thickness between 1.5 and 13.7 m (5 and 45 ft).

The anhydritic unit shown in the upper part of the Dawson Bay Formation in Figure 49 does not necessarily correspond with the DB-5 member of Lane (1959). The distribution of the halite-impregnated beds below the Hubbard Evaporite in southeastern Saskatchewan was mapped by Lane (1959, Fig. 10).

Paleogeography, Elk Point evaporites

The present distribution of the Elk Point Group in the Interior Platform gives a fair idea of the original outline of the sedimentary basin. Although the southern and northeastern limits are erosional, there is enough evidence to suggest that the basin was initially landlocked and developed later into a large embayment.

A comparison of the principal facies distribution in the Lower and Upper Elk Point subgroups (figs. 25, 48) suggests that the Elk Point Basin was gradually filled with sediments and evaporites and that there was little supply of terrigenous material from the surrounding emergent areas. The facies map of the Lower Elk Point subgroup indicates that there were two landlocked subbasins in Alberta, separated by the eastward extension of the Peace River Arch. The facies map also shows that the evaporitic deposits in the northern part of the Interior Platform were separated by shelf carbonates from the marine deposits in the Mackenzie Mountains. This pattern suggests that the Elk Point Basin was invaded by the sea from the northwest and that the Tathlina Uplift may have played an important role in the history of the evaporitic basins to the southeast. Other paleotopographic high areas north of Tathlina Uplift, such as the Keele Arch (Cook, 1975), may also have restricted the inflow of seawater during periods of extreme evaporation.

The facies map of the Upper Elk Point subgroup indicates that the Tathlina Arch ceased to be a barrier during the Givetian Stage; the Peace River Arch, however, remained partially emergent. It has been suggested that the upper part of the Elk Point Group accumulated in an embayment with a narrow connection to the ocean in the northwest, where the carbonate facies acted as a barrier. Law (1955) proposed that the shelf carbonates in the southern part of the District of Mackenzie of the Northwest Territories included a barrier reef (the Presqu'île Formation), which migrated northward over older forereef deposits of the Pine Point Formation. The barrier reef restricted the circulation of seawater to the southeast, so that, during periods of extreme evaporation, salt and anhydrite could accumulate behind the barrier. This paleogeographic reconstruction is based on the assumption that, during the Givetian Stage, the region now known as the Canadian Shield was in part emergent (see Williams, 1984). Grayston et al. (1964), Bassett and Stout (1967) and Bebout and Maiklem (1973) have incorporated these ideas in a series of simplified facies maps showing prominent paleogeographic features of the Elk Point Basin at different time intervals.

Environment of deposition, Elk Point Group

From the preceding description of the evaporitic deposits of the Elk Point Group, it is evident that the evaporites accumulated under a variety of sedimentary as well as diagenetic environments. In order to infer the environment of deposition one must carefully separate out the primary depositional features, such as bedding, particle size, texture and grading, from secondary or diagenetic features related to recrystallization, replacement and leaching. One may deduce from a set of primary sedimentary structures that a particular deposit is of marine origin, but evidence from diagenetic features in the same deposit may also suggest that a substantial part of the deposit formed in a nonmarine environment.

Primary depositional structures are commonly preserved in anhydritic rocks (see figs. 38b, 45b, d, e). They include bedding laminae, scoured surfaces and desiccation fractures. Occasionally preserved are lithoclasts, pebbles, grains, peloids, oncoliths (Fig. 58b), and fossils (Fig. 55h, i). In the salt beds, primary depositional features are less commonly seen. They include bedding, laminae, "chevron" crystal structures and polygonal desiccation fractures.

Structures commonly observed in diagenetic anhydrite deposits are nodules, veins, and euhedral crystals (see Fig. 47). The anhydrite nodules have a variety of different

shapes and are commonly deformed by compaction. They locally form nodular or contorted beds. Occasionally one can demonstrate that they originated from fenestral (bird's-eye) voids or intrafossil porosity. Some desiccation fractures are filled with anhydrite (Fig. 47). The diagenetic or replacement anhydrite is commonly white and finely to coarsely crystalline. It can be demonstrated in some cases that during the recrystallization process the argillaceous or dolomitic residue of the original matrix has accumulated around the nodules (see figs. 54b, 55c).

Replacement of one evaporitic mineral by another is also regarded as a diagenetic feature. Occasionally, halite in the form of "hopper" or "chevron" crystals is replaced by anhydrite (see figs. 50e, 55d, e, f). In one example, anhydrite has partly replaced interbedded halite and anhydrite (Fig. 56b) and, in another, fragments of stromatolites are anhydritized (Fig. 45c). Halite occurs commonly as cement in pelletoidal dolostones (figs. 50g, 54e, i, 59b). In two cases, halite has formed nodules in which the original host rock is completely replaced (figs. 38b, 56d).

Another form of diagenesis is recrystallization. Almost all carbonates and evaporitic rocks of the Elk Point Group are partly or completely recrystallized. The original chevron halite crystals are rarely seen in salt beds. All fossils are recrystallized and commonly replaced by dolomite-anhydrite. From the above, it is clear that interpretation of environment should focus on both the primary depositional features and secondary diagenetic features.

Primary evaporitic deposits. Previously discussed evidence indicates that the primary deposits of the Elk Point Group include both precipitates and sediments. The precipitates are composed of halite. Beds of coarsely crystalline sulphates, similar to the selenite crystals described by Hardie and Eugster (1971) from the Upper Miocene Solifera Series of Sicily, which are primary precipitates from a body of saline water, are unknown in the Elk Point Group. The bedded and laminated deposits composed of dolomitic or anhydritic shale and dolomitic or argillaceous anhydrite may be regarded as sediments if they include recognizable sedimentary structures. They may have been originally composed of very fine grained gypsiferous carbonates and are considered to be erosional products of older, unconsolidated, nearshore, sabkha-like deposits in which gypsum and anhydrite occurred as primary and secondary precipitates. During the extreme evaporitic conditions of the early Middle Devonian, the water in the Elk Point embayment was so saline that not all erosion products composed of calcium sulphate were dissolved, but, instead, were deposited as sediments in the central part of the embayment. Alternatively, one may argue that the bedded anhydrites originally were carbonates cemented by gypsum and were later transformed into anhydrite by diagenesis.

Sulphates. It is difficult to estimate the relative abundance in per cent between the "sulphate sediments", the secondary sulphate deposits, and the carbonate sediments, but it is evident that the "sulphate sediments" only form a small part of the total. In the subsurface, the sulphate sediments occur in the form of anhydrite. They may be described as mudstones, wackestones and floatstones, according to the classification of Dunham (1962), which was later modified by Embry and Klovan (1971, Fig. 2). The three most common lithologies are dark grey, laminated mudstone; light brown, laminated mudstone or wackestone; and greenish grey argillaceous mudstone or anhydritic shale.

The dark grey, laminated anhydrite-mudstone is dolomitic and dark coloured bituminous material is responsible for the discontinuous or continuous laminae. These mudstones were previously described as "laminites" (see Fig. 50a, b, c) by Fuller and Porter (1969a), Wardlaw and Reinson (1971), Bebout and Maiklem (1973), Davies and Ludlam (1973), and Corrigan (1975). They are very similar to and commonly grade into dolomitic or calcitic "laminites" that contain calcispheres or ostracodes. They are occasionally intercalated with thin beds containing lithoclasts (Corrigan, 1975). The carbonate laminites and their anhydritic equivalents probably accumulated in relatively deep water (Bebout and Maiklem, 1973).

The light brown, laminated mudstone or wackestone is an anhydritic dolostone with thin, delicately laminated interbeds (figs. 47, 59e). The beds may include scoured surfaces and granule-sized dolomitic lithoclasts (figs. 38c, 45d, 59e, 61e). The bedding is commonly disturbed by folds or broken up by vertical cracks filled with secondary anhydrite. The mudstones resemble the laminar-fenestral, carbonate wackestones which contain peloids, lithoclasts, calcispheres and ostracodes, and which are commonly interbedded with stromatolites. These deposits are probably of a shallow water, intermittently exposed environment (see Bebout and Maiklem, 1973; Meijer Drees, 1980).

The greenish grey, argillaceous anhydrite or anhydritic shale is widely distributed as thin beds in the salt but is more prominently present in the nearshore facies of the Prairie Evaporite Formation south of the Peace River Arch. In this nearshore facies, the argillaceous beds contain light coloured, anhydritic inclusions with algal filaments (see figs. 55g, h, i; 61c), abundant peloids, mud clasts and lithoclasts, and occasionally include stromatolites. They are interpreted as nearshore, shallow-water deposits.

The other types of sedimentary rocks in the Elk Point Group include anhydritic floatstones, crosslaminated anhydrite-mudstones (see Fig. 45b), anhydritic stromatolites, and coarse grained, anhydritic redbeds with crystals (see Fig. 38e). These and other types of sulphate sediments are not so widely distributed as the mudstones but they indicate that, in the Elk Point embayment, calcium sulphate in the form of gypsum mud, gypsum cement, or gypsum crystals was a stable deposit.

Chlorides. The maps and cross-sections presented in this report indicate that the salt beds occur in the central part of the Elk Point Basin and are largely absent in the nearshore facies. One would expect the reverse, because the conditions under which halite precipitates from a body of water are much more favourable along the margin than in the centre of the basin. The explanation probably is that, in the nearshore environment, the salt is dissolved by occasional rainstorms and brought back in the form of ions to the brine in the central part of the basin. Only when the brine is saturated does salt precipitate in the central part of the basin and there it is protected from dissolution by the brine above. The accumulation of salt can only proceed if there is a supply of ions, a relative sea level rise, and evaporation. Each influx of fresh seawater probably dissolved a large part of the previously precipitated salt, but the presence of thick salt deposits indicates that not all salt was dissolved. This mechanism, named "evaporative drawdown" (Maiklem, 1971), explains why the salt accumulated first in topographic depressions. The idea that each evaporative cycle is represented by a layer of salt is probably too simplistic.

Relatively little is known about the regional variability in the lithology of the Elk Point salt beds. Available information from scattered cores suggests that there are several types of salt which may be classified as chemical precipitates.

The thick bedded, relatively pure deposits of rock salt in the Elk Point Group are interpreted as primary, chemically precipitated deposits. Some salt beds have retained their original depositional features, such as laminae, chevron structures (Fig. 50f), and dissolution surfaces (Fig. 59e). These structures were described by Wardlaw and Schwerdtner (1966) and Fuller and Porter (1969a, Fig. 16). They are locally intercalated with thin beds of anhydritic mudstone which are ripple marked (Fig. 56f). These salt beds probably accumulated in relatively deep water. Other salt beds are reddish brown, do not contain remnants of the original halite crystals and include greenish grey and reddish brown mottled, anhydritic shale beds, locally with polygonal syneresis cracks (see Fig. 57c). These salt beds probably accumulated in relatively shallow water and may have been subaerially exposed for short periods of time. The reddish brown salt beds containing potash minerals are completely recrystallized and the space between the salt crystals is commonly occupied by reddish brown or greenish grey shale. The interbedded shale beds and the underlying salt beds are commonly cut by polygonal desiccation fractures (see figs. 56a, 57a, b); and the fractures are filled with sylvite. The salt beds probably accumulated in much the same way as the other salt beds but they were probably exposed for long periods of time. The presence of potash salts such as sylvite and carnallite suggests that during the period of exposure the environment was devoid of free circulating water. The accumulation of the potash salts probably occurred after the recrystallization of halite from upward moving groundwater brines (for more detail see Holter, 1969). The reddish brown shale beds may be regarded as eolian deposits.

Holser, Wardlaw, and Watson (1972) discussed the implications of the previously reported analysis of the bromine content of several salt deposits in the Elk Point Group. Wardlaw and Watson (1966) found that the clear, semi-transparent halite of the Lotsberg and Cold Lake formations of the Elk Point wells in east-central Alberta is characterized by the absence of disseminated sulphate and extremely low content of bromine, which occurs in solid solution in chlorides (Schwerdtner and Wardlaw, 1963). The bromine content is so low that these salt beds could not have precipitated directly from seawater. They must have been recycled by nonmarine water before they were finally deposited or they must have originated from a nonmarine brine. The bromine content of the Cold Lake Salt in northern Alberta is unknown, but, in the southern part of the District of Mackenzie of the Northwest Territories, the Cold Lake Salt in the Davidson Creek well (Lat. 62°11'45"N, Long. 118°15'05"W) has a bromine content that is normal for salt beds of a marine origin (Holser et al., 1972).

The salt beds of the Prairie Evaporite Formation in east-central Alberta and southern Saskatchewan contain three types of salt: chevron halite, clear halite, and brown halite. These three types of rock salt have a bromine content in the usual range for chlorides of marine origin, although they include intervals with anomalous bromine to chlorine ratios (Holser et al., 1972; Wardlaw and Watson, 1966). Although the texture of the rock salt suggests that the chevron halite is primary and the clear halite is secondary (in places it has replaced the chevron halite), the clear halite has a higher bromine content than the chevron halite (Wardlaw and Schwerdtner, 1966). The clear halite also has a higher bromine content than the brown halite (Wardlaw and Watson, 1966).

Secondary evaporitic deposits. Under extremely arid conditions a body of water will not only lose fluid by surface evaporation but also by lateral movement of groundwater. The groundwater moves sideways, downwards, and upwards through the porous sediments along the margin of the basin under the influence of a hydraulic gradient, and evaporates just below, or at, the land surface. If the groundwater contains minerals, some of them will precipitate outside the body of water on land as subsurface deposits just above the average groundwater level. An example of such a mineral deposit is the nodular anhydrite found in the shallow subsurface of Recent carbonates in the sabkhas of the Trucial Coast of the Persian Gulf. These deposits were described by Shearman (1963), Kinsmen (1966), Butler (1970) and others.

Another type of groundwater movement was named "evaporative pumping" by Hsü and Siegenthaler (1969). It occurs in porous sediments along the margin of a body of water under the influence of evaporation on land. Water flows in the shallow subsurface from the body of water through the porous sediments and evaporates near the land surface.

Work in the intertidal and supratidal deposits along the Trucial Coast has established the fact that the flow of mineral-rich groundwater plays an important role in the accumulation of secondary evaporitic minerals (see Patterson and Kinsman, 1981). Through the process of evaporative pumping, evaporitic minerals can be carried beyond the edge of the body of water. If this body is connected to the sea and evaporation occurs under extreme, arid conditions, saline water will enter the groundwater system and evaporitic minerals may accumulate as secondary deposits in the shallow subsurface around the margin of the embayment. Under conditions of extreme evaporation, the embayment will gradually diminish in size and the surface and groundwater system may become highly saline. Under such circumstances, secondary carbonates, sulphates, and chlorides may accumulate in former lake sediments, not only in the shape of nodules and nodular beds, but also as cement. Not much is known about the process of cementation, but it can be demonstrated that a vast amount of carbonate and sulphate was precipitated in the Elk Point sediments. Porosities in the original carbonate muds and sands probably ranged between 40 and 70 per cent, but porosities in the lithified Elk Point carbonates seldom exceed 8 per cent.

It is important to point out that the surface water represented only a small proportion of the total amount of water contained in the evaporitic basin. Thus, in an arid climate, a surficial influx of fresh seawater is probably not large enough to dilute the saline groundwater system. However, the influx of fresh seawater on the surface may be large enough to leave a deposit of marine sediments. It is also evident that the influence of occasional rainstorms is mainly felt near or at the surface and results in transport of the most soluble evaporitic minerals toward the least elevated part of the sedimentary basin. Both processes play an important role in the regional distribution of the evaporitic minerals.

Anhydrite. The secondary anhydrite deposits of the Elk Point Group include anhydritized rocks, anhydrite nodules, nodular-bedded anhydrite, mosaic-anhydrite, recrystallized anhydrite, crystallopic anhydrite, and anhydrite or gypsum veins.

Some rocks were partly or completely altered to anhydrite without much change in structure. Examples of stromatolites and anhydritized halite crystals have been recorded (see figs. 43c, 50e, 55f). These examples demonstrate how difficult it is to classify some anhydrites.

Nodular anhydrite displacing fossiliferous dolostone is commonly found in the Muskeg Formation in beds adjacent to Keg River reefal mounds. It also occurs in the undivided Shell Lake - Whitkow beds of the Prairie Evaporite Formation where it replaces fossiliferous, pelletaloid or pisolitic dolostone. Nodular anhydrite also occurs in the upper parts of the Winnipegosis and Keg River formations where it has replaced brecciated dolostone, including vugs filled with laminated sediment (see Bebout and Maiklem, 1973; Corrigan, 1975; Wardlaw and Reinson, 1971).

Nodular and nodular-bedded anhydrite occur in the carbonate sediments of the lower Muskeg Formation, the lower part of the Prairie Evaporite Formation (Whitkow and Shell Lake members), in the Ratner Member of the Winnipegosis Formation (Wardlaw and Reinson, 1971), and in the Bear Rock Formation (Meijer Drees, 1980). These nodular beds are not strongly displacive, are commonly deformed by compaction and occur in limestone, dolostone, or anhydritic dolostone. Laminated beds containing scattered nodules commonly grade upward into nodular beds, pseudo-contorted nodular beds, and massive, nodular-mosaic anhydrite. The upward change in bedding structure is accompanied by a change in lithology from dolomitic to non-dolomitic anhydrite. Detailed observations of transitional contacts between non-anhydritic and anhydritic laminites suggests that the anhydrite makes its first appearance as a cement in thin, pelletaloid interbeds and as a fenestral void filler. With the increase of the anhydrite content, nodules are formed which coalesce into nodular beds and mosaic-anhydrite (see Fig. 50c). In mosaic-anhydrite, the original dolomitic host rock occurs as partings between the nodules (see Bebout and Maiklem, 1973, Fig. 3). The presence of scattered interbeds of light brown, anhydritic dolomite-mudstone suggests that the nodular anhydrite has displaced a mixture of carbonate and sulphate sediments of shallow water origin.

Because the nodular and nodular-bedded deposits of the Elk Point Group are similar to sabkha anhydrite, some geologists concluded that they were deposited by upward moving groundwater during periods of evaporative drawdown (Fuller and Porter, 1969a, b; Shearman and Fuller, 1969; Bebout and Maiklem, 1973). Other geologists have argued that not all nodular and nodular-bedded anhydrite deposits in the Elk Point Group resemble sabkha anhydrite (Wardlaw and Reinson, 1971; Davies and Ludlam, 1973), and that the nodular-bedded anhydritic "laminites" are recrystallized sulphate precipitates that accumulated in relatively deep water as interbeds of anhydrite carbonates. The absence of anhydrite beds with crystal structures similar to the ones described by Hardie and Eugster (1971) indicates, however, that the nodular-bedded laminites are not primary precipitates in relatively deep water. If the evaporitic succession is well preserved and not extensively recrystallized, examples can be found of both the displacive, sabkha type anhydrite and the recrystallized, nodular-bedded, shallow water, sulphate-rich sediments (see Fig. 47). However, in most anhydrite deposits the original structures are destroyed by recrystallization and compaction and the distinction between the two types cannot be made.

Recrystallized finely to coarsely crystalline, "felted" anhydrite, in which the crystals are aligned (see Maiklem et al., 1969), is commonly present in evaporites in or near the Cordilleran Orogen. There, the evaporitic deposits have been buried deeply and have been locally disturbed by folding, faulting and thrust faulting. The recrystallization has affected both the anhydrites of sedimentary origin and those of diagenetic origin.

Crystallotopic anhydrite (Maiklem et al., 1969) occurs as scattered crystals or as crystal clusters, commonly along bedding planes, fractures or stylolites in carbonate rocks (see figs. 45c, 47, 54g). The crystals are not deformed by compaction and this fact suggests that the anhydrite accumulated in a host rock that was already lithified.

Deposits of anhydrite or gypsum, in the form of veins, are present below the sub-Cretaceous unconformity and in the shallow subsurface. In the subaerial environment, anhydrite recrystallizes to gypsum and is easily dissolved in groundwater. The dissolution of evaporites in the subsurface results in the collapse of overlying beds. Fractures in the collapse breccia are commonly filled or lined with gypsum. The collapse breccia deposits are commonly present in the Devonian outcrop belt and in the nearby subsurface just southwest and west of it, in the Bear Rock Formation and Meadow Lake Beds. They are also present in the subsurface of southern Saskatchewan near the International Boundary. The breccia deposits below the sub-Cretaceous unconformity originally were gypsum, but, because these beds were buried after their formation one may expect anhydritized gypsum-vein deposits similar to those described by Kendall (1975) from the Mississippian strata.

Salt. The secondary salt deposits of the Elk Point Group include beds cemented and partly replaced by halite (see figs. 38b, f; 45a; 50g; 54g; 56b, c, d; 58b, c, d; 59a, b, c, d, g, h; 61a), potash salts in polygonal desiccation cracks (Fig. 56a), potash beds composed of red carnallite and red sylvite (Fig. 57d), potash-free halite bodies ("salt horses") in potash beds, and the vein-like deposits related to fractures (see Fig. 56c). The volume of the secondary salt deposits is small in comparison with the volume of salt of primary origin.

Halite occurs as cement and void filler in anhydritic and dolomitic rocks of sedimentary origin (see figs. 38b; 45a; 50g; 54e, i). It has filled desiccation fractures (Fig. 57e) and fenestral voids and locally has displaced the host rock (see Fig. 58e). This type of halite may be regarded as early diagenetic. Halite is also present in pelletaloid or fossiliferous carbonates of the Elk Point Group where it has plugged the porosity. This type of halite is a late diagenetic deposit.

The deposits in the vertical structures in the Prairie Evaporite Formation below the White Bear marker, and in the large polygonal structures in the potash beds (figs. 57b, c) include clear halite and red carnallite or halite and red sylvite. It is assumed that these structures are large mud cracks formed during periods of subaerial exposure. The cracks probably served as access routes by which downward-moving surficial brines entered the shallow subsurface to initiate the deposition of secondary minerals.

The potash zones in the Prairie Evaporite Formation have transitional contacts with the underlying and overlying salt beds; they are bedded, and there is evidence that they originally were primary, cyclic deposits (Klingspor, 1958). However, detailed petrographic studies by Stewart (1956), Schwerdtner (1964) and Wardlaw (1968), and information obtained by Schwerdtner (1964) and Wardlaw (1968) from bromine and rubidium contents of the various chlorides, and chemical considerations (Wardlaw, 1970), suggest that the potash salts are secondary deposits. Red carnallite is a relatively late secondary mineral because it has replaced sylvite and halite. The red sylvite is derived from red carnallite by leaching of magnesium chloride.

It is assumed that during periods of subaerial exposure, surface water, either of marine or meteoric origin, moved from the more elevated to the less elevated regions in the central part of the desiccated Elk Point Embayment. The water would be rich in potash and magnesium chlorides by the time it reached the topographic lows where it would accumulate on the surface or in the shallow subsurface. The surficial brines would react with the primary potash salt deposits (according to Schwerdtner, 1964, mainly colourless carnallite and sylvite) above the saline groundwater table, during periods of extreme drought, and red carnallite would precipitate. During wet periods, the red carnallite crystals may have been partly leached by a rise in groundwater level and red sylvite may have formed. The rise and fall of the groundwater table would distribute the potash salts in a relatively thin, but widespread, stratiform zone. The zone does not necessarily follow the original bedding of the host rock (see Holter, 1969).

Detailed work by Keyes and Wright (1966) and McIntosh and Wardlaw (1968) on the "salt horses" in the potash beds of the Prairie Evaporite Formation near Esterhazy suggests that the halite in these features has replaced potash ore. Details of stratification can be traced from the potash beds into the smaller "salt horses", suggesting replacement. Additionally, since the bromine content of the halite and sylvite in the "salt horses" is substantially higher than the bromine content in the adjacent ore beds, the halite in the "salt horses" is not a remnant of a primary salt deposit. The "salt horses" may be the result of reaction between residual brines in the potash ore beds and a brine only saturated in sodium chloride. The latter brine may have entered the Prairie Evaporite Formation during periods of epeirogenic uplift, when Mississippian and Devonian strata were tilted and partly eroded.

Red, fibrous vein deposits of halite (Wardlaw and Watson, 1966) are present in the "Basal Red Beds" in the Lotsberg Formation, the White Bear member of the Prairie Evaporite Formation, and in the lower redbed member of the Dawson Bay Formation. Some of the veins are salt-filled desiccation fractures, others may be fractures of tectonic origin.

Structural geology, Elk Point Group

Before selecting a datum to show the present-day structural configuration of Elk Point Group evaporites, it is important to be cognizant of the depositional structures (such as bedding, facies changes, erosional unconformities, and depositional hiatus) which make up the Elk Point Basin's regional depositional framework.

From the structural cross-sections (figs. 26-34), it is evident that the base of the Elk Point Group has a different structural configuration than the top. There are no structure contour maps available of the base of the Elk Point Group (the pre-Devonian unconformity). The formational or member boundaries within the Elk Point Group do not extend across the entire study area and are not useful for regional structural mapping. Thus, it was decided to map a surface near the top of the Elk Point Group. In northern Alberta, the base of the Watt Mountain Formation is a well marked, widespread surface. It overlies the Sulphur Point and Muskeg formations and probably coincides with a major depositional hiatus. In east-central Alberta, the top of the Muskeg Formation is in mappable continuity with the top of the Dawson Bay Formation. It would thus have been desirable to combine the base of the Watt Mountain Formation and the

top of the Dawson Bay Formation in one map. However, for practical reasons, this was not possible and reproduction of the structural contour map of the Prairie Evaporite Formation in Saskatchewan (published by Holter, 1969) was advised. With data supplied by Barnatyne and McCabe (1966), the eastern portion of this map was updated and extended to include Manitoba. Although the top of the Prairie Evaporite Formation in east-central Alberta lies 6 to 15 m (20-50 ft) below the base of the Watt Mountain Formation, and the discrepancy between the two surfaces in south-central Saskatchewan is more than 67 m (220 ft), the combination of the two maps gives a fair impression of the structural configuration of the Upper Elk Point beds in the Southern Plains (see Fig. 63). The Elk Point beds in Manitoba, Saskatchewan, and Alberta dip to the southwest. The dip of this homocline increases toward the southwest and west from about 3.9 to 7.8 m/km (20 ft to about 40 ft/mi), and the direction of the dip varies locally between southwest and south-southwest (see Fig. 63).

In northeastern Alberta and central Saskatchewan, where the Prairie Evaporite Salt is absent due to dissolution, structural contour lines are not drawn because of a lack of information. In this region, the beds overlying the salt have collapsed. Carrigy (1959, Fig. 5) published a structural contour map of the Prairie Evaporite Formation in the Fort McMurray area and indicated the presence of northwest-trending anticlinal and synclinal structures. The axis of the anticlinal structure coincides with the southwestward limit of salt leaching; the axis of the syncline occurs northeast of the anticline and marks the place where all the salt has been dissolved. Figure 63, and structural maps of Upper Devonian markers in the Lloydminster area (Meijer Drees, 1985), also show the presence of anticlinal and synclinal structures that parallel the zero edge of the salt northeast of the salt edge in east-central Alberta and Saskatchewan.

Irregularities of a local nature are present in the Rainbow and Zama lake areas of northwestern Alberta near the carbonate mounds of the Keg River Formation. These anomalies may be partly the result of differential compaction between evaporites and reefal carbonates, or due to the fact that, in the vicinity of the reefal mounds, some salt has been dissolved. Other irregularities in the contour lines (in Fig. 63) for Alberta and Saskatchewan are the result of paleotopographic features of the pre-Devonian surface.

The north-northwesterly trend of the structural contour lines in northern Alberta (Fig. 63) continues into the extreme southern part of the District of Mackenzie. However, north of Latitude 60°30', the contour lines change direction to a more westerly trend and the lines stop near the northern edge of the Presqu'île Barrier reef. North of this carbonate facies, the Upper Elk Point subgroup is only represented by equivalents of the Pine Point Formation (see Fig. 23). Here, the structural configuration of the Elk Point Group (in Fig. 63) is shown by contour lines which represent the upper surface of the Lonely Bay or the Nahanni Formation. The elevation of this surface is about 91 m (300 ft) below the base of the Watt Mountain Formation.

Figure 63 indicates that the structural configuration of the Elk Point strata in the southern part of the District of Mackenzie is an extension of the Alberta homocline, and that there is a large, complex structural high located north of the Mackenzie River. This structural high is also present on the structural contour map of the Precambrian surface (Fig. 4). The axis of the high trends approximately southwest-northeast and passes through Lac La Martre.

On the southeastern flank of the high (Fig. 26), the Elk Point strata overlie granitic rocks of Precambrian age. On the northwestern flank the granitic rocks are overlain by a wedge of sedimentary rocks of Proterozoic and early Paleozoic age. The cross-section also indicates that the structural high is cut off at the top and overlain by almost flat-lying Cretaceous beds. This situation and other information (see Meijer Drees, in press) suggest that the structural high is a tectonic uplift of post-Mississippian and pre-Cretaceous age.

The structural contour lines in Figure 63 show several relatively small anomalies. The irregularities in the 2000 foot contour line northwest of Tathlina Lake are due to irregularities of the Precambrian surface (see Fig. 4), and the presence of northeastward trending faults (see Williams, 1977). Similar irregularities are present in the -1000 foot and -5000 foot contour lines.

The circular anomaly located just north of the boundary between British Columbia and the Northwest Territories is the Celibeta High, a tectonic uplift in which pre-Cretaceous and Cretaceous beds were deformed during the Laramide Orogeny (see Williams, 1977).

The large structural anomaly north of the Liard River is a pre-Devonian paleotopographic feature similar to Tathlina Uplift (see Figs. 30, 35).

The two elongate anomalies north of the Mackenzie River and east of the southern Franklin Mountains are anticlinal structures related to the Laramide Orogeny. The sharp increase and the change in direction of dip in the region just east of the Franklin Mountains is also related to the Laramide Orogeny and indicates the presence of the Nahanni and McConnell thrust faults.

3. Evaporites of Late Devonian age

Introduction

The Upper Devonian evaporites are interbedded with carbonates and only occur in the southern part of the Interior Plains and Rocky Mountains. This interbedded succession overlies the Middle Devonian succession with apparent conformity and is in turn conformably overlain by beds of Mississippian age. In the Interior Plains region southwest and west of the Canadian Shield, Mississippian strata are absent and the Upper Devonian carbonates are erosionally overlain by Cretaceous strata. In northeastern Alberta and the District of Mackenzie, Upper Devonian rocks are exposed locally (see Fig. 2).

The Upper Devonian evaporites and interbedded carbonates are widely distributed in southern Saskatchewan and Alberta. In Alberta, the evaporitic units change laterally to carbonates in a northwesterly direction. Because this facies change occurs at several levels within the succession, and was influenced by the presence of reefal mound deposits, the stratigraphy of the Upper Devonian succession in southern Alberta is complicated. In southern Saskatchewan and North Dakota, the evaporitic facies is dominant and the stratigraphy of the Upper Devonian succession is relatively simple. The evaporitic beds and interbedded carbonates are exposed in the southern Rocky Mountains, in northern Montana, and in North and South Dakota. One evaporitic unit is exposed in northeastern Alberta.

The evaporites accumulated in a shallow sea or embayment, northwest of a landmass situated in the central part of the United States. The epeiric sea was formed as a result of the continued relative rise in sea level that started during the Middle Devonian period. Although the epeiric sea was in open connection with the ocean to the northwest and west, the flow of water to the landward side of that sea was restricted by the development of carbonate banks, reefal mounds, and barrier reefs. Northwest and west of these carbonate deposits, the environment was normal marine, but southeast of the carbonate deposits the environment was at times highly saline. The climatic and geologic conditions during the Devonian Period must have been very stable, because the evaporitic units can be mapped over large areas in the southern part of the Interior Plains and show very little change in thickness or lithology.

Distribution and thickness

The Upper Devonian succession in the subsurface of the Canadian Interior Plains was mapped by Bassett and Stout (1967), the Committee on Slave Point and Beaverhill formations (1964), and by Belyea (1964). The succession was mapped and described in the northwestern part of the Interior Plains of the United States of America by Sandberg and Mapel (1967).

In the northern part of the Interior Plains of Western Canada, the Mississippian strata are absent and the Upper Devonian succession is incomplete. Only in the southwestern part is the Upper Devonian succession complete. The uneroded thickness of the Upper Devonian strata varies between 304.8 and 975.4 m (1000 and 3200 ft), and the isopach map of McCrossan and Glaister (1964, figs. 6-13) shows a gradual increase in thickness from south to north across the Interior Plains. The succession reaches a maximum thickness of over 914.4 m (3000 ft) in central Alberta. In the area southeast of Fort St. John in northeastern British Columbia, the thickness is less than 152.4 m (500 ft), because the Peace River Arch was still emergent during the early part of the Upper Devonian Period. North of the Peace River Arch, the thickness of the Upper Devonian strata increases northward to over 914.4 m (3000 ft) in northwestern Alberta and adjacent parts of the Northwest Territories.

Bassett and Stout (1967) mapped the thickness and facies distribution of the Upper Devonian beds belonging to the Frasnian and Famennian Stages in the northern and southern Interior Plains. The thickness of the beds belonging to the Frasnian Stage varies between less than 30.5 and more than 914 m (100 ft and 3000 ft). In central Alberta, the Frasnian strata are more than 762 m (2500 ft) thick in a depocentre north of Edmonton, and more than 914 m (3000 ft) thick in the northern part of northeastern British Columbia. The thickness of the uneroded Famennian strata in the Interior Plains varies from less than 76.2 m (250 ft) in Saskatchewan and Manitoba to more than 228.6 m (750 ft) in northeastern British Columbia. The presence of the Peace River landmass is shown only on the isopach map of the Frasnian beds; the presence of a landmass west of Inuvik is indicated on both maps.

Evaporitic deposits are present in the southeastern part of the Interior Platform. They are interbedded with carbonates and individual deposits have been traced over relatively large distances. Two cross-sections (figs. 29, 34) show truncation below the pre-Jurassic and pre-Cretaceous unconformities.

ALBERTA PLAINS										SASKATCHEWAN	
NORTHEASTERN			CENTRAL				SOUTHERN				
WABAMUM GROUP			WINTERBURN GROUP	WABAMUM GROUP		BIG VALLEY FORMATION		BIG VALLEY FORMATION		THREE FORKS GROUP	BIG VALLEY FORMATION
				STETTTLER FORMATION		STETTTLER FORMATION		STETTTLER FORMATION			TORQUAY FORMATION
WINTERBURN GROUP	GRAMINIA FORMATION			WINTERBURN GROUP	GRAMINIA FORMATION	Siltstone member	CROWFOOT FORMATION				
	CALMAR FORMATION					Blue Ridge Member					
	NISKU FORMATION				CALMAR FORMATION						
IRETON FORMATION			WOODBEND GROUP	NISKU FORMATION						BIRDBEAR FORMATION	
HONDO FM		Camrose Mbr									
GROSMONT FORMATION		LEDUC FM		IRETON FORMATION							
COOKING LAKE FORMATION		DUVERNAY FORMATION						DUPEROW FORMATION			
		COOKING LAKE FORMATION		Majestic Lake Member							
WATERWAYS FORMATION			BEAVERHILL LAKE GROUP	WATERWAYS FORMATION				BEAVERHILL LAKE GROUP		SOURIS RIVER FORMATION	
SLAVE POINT FORMATION				SWAN HILLS FORMATION							
WATT MOUNTAIN FORMATION				WATT MOUNTAIN FORMATION		WATT MOUNTAIN FORMATION		WATT MOUNTAIN FORMATION		First Redbed	
MUSKEG FORMATION			DAWSON BAY FORMATION		DAWSON BAY FORMATION		DAWSON BAY FORMATION		DAWSON BAY FORMATION		
			PRAIRIE EVAPORITE FORMATION		PRAIRIE EVAPORITE FORMATION		PRAIRIE EVAPORITE FORMATION		PRAIRIE EVAPORITE FORMATION		

Figure 64. Table of Upper Devonian formations, Alberta and Saskatchewan.

GSC

Stratigraphy

Upper Devonian strata are exposed in the Rocky Mountains. In this area, they consist mainly of carbonates and evaporitic deposits are not present. Some of the rock units mapped in the southern Rocky Mountains have been recognized in the subsurface of southern Alberta (see Belyea and McLaren, 1957; Belyea, 1964). These include the Cairn and Southesk formations of the Fairholme Group (see Fig. 64).

Geologists working in the subsurface of the southern Interior Plains first applied the subdivision used by Peale (1893) in the outcrop area of Montana, but later established their own subdivisions. At present, a large number of formation names are recognized in the subsurface. In this

report, we shall only discuss the map units used in the evaporitic facies and their equivalents in the carbonate facies.

Baillie (1953) used several thin, widespread, argillaceous marker beds to subdivide the evaporitic beds of Late Devonian age in the subsurface of the southern plains into three groups. He proposed the Manitoba, Saskatchewan, and Qu'Appelle groups. Sandberg and Hammond (1958) introduced a subdivision which correlates with the subdivision used in the outcrop area of Montana. According to this subdivision, the Upper Devonian succession includes, in ascending order: the Souris River, Duperow, Birdbear, and Three Forks formations. The Duperow and Birdbear formations together correlate with the Jefferson Formation of Peale (1893) and Haynes (1916). The Three Forks Formation of Sandberg and Hammond (1958), however, does

not include the sandstone beds that form the upper unit of Peale's original Three Forks shale. The Three Forks Formation in the subsurface was thus elevated to group status by Christopher (1961) to include the Torquay, Big Valley, and Bakken formations. Since the upper part of the Bakken Formation is of Mississippian age, the term Three Forks Group is omitted from the correlation chart in Figure 64. Previous authors have subdivided the Devonian succession in Saskatchewan into the Souris River, Duperow, Birdbear, Torquay, and Big Valley formations.

Upper Devonian strata in central Alberta were first subdivided by the geological staff of Imperial Oil (1950) and additional map units were introduced by Belyea (1955), Wofor and Andrichuk (1956), and Belyea and McLaren (1957). The subdivision used in this report is shown in Figure 64 and includes the Slave Point, Waterways, Cairn, Southesk, Crowfoot, Stettler, and Big Valley formations.

Evaporitic deposits occur in the Souris River, Duperow, Birdbear, Torquay, Slave Point, Southesk, Hondo, Crowfoot and Stettler formations (see Fig. 65). They are also present in the upper part of the Winterburn Group.

Evaporitic deposits

The evaporitic deposits of Late Devonian age include interbedded anhydrite and carbonate, anhydrite, gypsum, halite and redbeds. These evaporites occur as relatively thin, widespread units separated from each other by argillaceous, fossiliferous, and peloidal carbonates (see Fig. 65). Detailed subsurface correlations based on information from borehole logs and cores suggest that the argillaceous beds, carbonates, and evaporites follow each other in a vertical sequence that is repeated with many variations. The term cyclic is widely used to characterize the evaporitic sequence (see Wilson, 1967).

In the following discussion, the evaporitic deposits of the Slave Point, Souris River, Duperow, Torquay, Stettler, and Hondo formations will be described. No original work was done on the evaporites and all information discussed below was compiled from previously published reports.

Evaporites of the Slave Point Formation. In northern and northeastern Alberta, the Slave Point Formation includes a distinct basal unit, named the Fort Vermilion Member (Law, 1955). This member is readily mapped in the Zama Lake area and consists of about 7.6 m (25 ft) of algal-laminated and fine pelletoidal limestone with abundant calcispheres and secondary anhydrite nodules (McCamis and Griffith, 1967). The anhydritic deposits become thicker toward the east and are interbedded with dolostone and limestone. The Fort Vermilion Member extends southward into east-central Alberta. The member is traced and its depositional limits are indicated on the cross-section in figures 26, 27, 28, 31, 32, 39 and 53. There are no published maps available showing the distribution and thickness of the member.

Norris (1963) raised the Fort Vermilion Member to formational status and described it from exposures along the Peace River. In the exposures, it consists of thin to thick and evenly bedded, white gypsum with thin interbeds and laminae of varicoloured, commonly bluish grey and light brown, impure gypsum. Light brown, fine- to medium-grained, thinly bedded limestone and dolomitic limestone units, from 0.6 to 1.5 m (2-5 ft) thick, are present. In this area, the Fort Vermilion Member is between 27.4 and 36.6 m (90 and 120 ft) thick.

Evaporites of the Souris River Formation. Walker (1959) mapped the Souris River Formation in the subsurface of southern Saskatchewan. He recognized three members separated by thin, widespread shale beds. The three members were named by Lane (1964), in ascending order, the Davidson, Harris, and Hatfield members. The Davidson Member includes the Davidson Evaporite of Baillie (1953), a widely distributed unit of salt and anhydrite. The Harris and Hatfield members include several units of halite and anhydrite, of which only three have been named (see Fig. 65).

The Davidson Evaporite was mapped by Lane (1964) and by Kendall (1976b). It is the upper unit of the Davidson Member and locally includes two salt beds. The Davidson Evaporite (Fig. 66) varies in thickness between 0 and 63.7 m (209 ft). The salt is up to 61.0 m (200 ft) thick in the area north of Moose Jaw and overlies different lithologic sub-units of the underlying B unit of the Davidson Member in the central part of the basin (see Lane, 1964, Fig. 12). This suggests that the salt accumulated in a paleotopographic basin. Near the margin of the basin, the salt is underlain or is interbedded with anhydrite and dense crypto- to micro-granular dolostone (Lane, 1964). The salt is a colourless, coarsely crystalline halite and includes minor amounts of greyish green, dolomitic mudstone.

The Harris Member overlies the Davidson Evaporite with a sharp, disconformable contact and includes, at the base, a widespread, greyish green and maroon shale marker. The shale grades upward into a limestone bed 3 to 6 m (10-20 ft) thick, which locally is overlain by up to 7.3 m (24 ft) of salt. This is the "lower Harris halite" (see Fig. 67) and it is overlain by a succession composed of cyclic deposits (including limestone, dolostone and anhydrite), which vary in thickness between 24.3 and 42.7 m (80 and 140 ft). The interbedded unit includes, locally, at the top, a salt bed, the "upper Harris halite". The "upper Harris halite" reaches a maximum thickness of 6.4 m (21 ft) in the area southeast of Saskatoon (see Fig. 68).

The Harris Member is sharply overlain by a thin shale marker which is included with the Hatfield Member. The Hatfield Member includes shale, argillaceous limestone, limestone, and dolostone. In the lower part of the member, interbeds of anhydrite or salt are present. The salt occurs locally in the upper part of the second evaporitic cycle. It was mapped by Land (1964, Fig. 15) as the "Beechy halite" in southern Saskatchewan and reaches a maximum thickness of 9.8 m (32 ft) in the area southwest of Saskatoon (see Fig. 69).

Evaporites of the Duperow Formation. Kent (1963) studied the Duperow Formation in southwestern Saskatchewan and recognized three members: an unnamed basal member, later subdivided into the Elstow and Saskatoon members (Kent, 1968), and the Wymark and Seward members. Evaporitic deposits, in the form of anhydrite and halite, are present in these members.

Dunn (1975) described the Duperow Formation in southeastern Saskatchewan and subdivided the formation into four unnamed units, numbered 1 to 4. Unit 1 corresponds to the basal member of Kent (1963) and the lower part of the Wymark Member. Unit 2 is equivalent to the middle part of the Wymark Member, Unit 3 includes the upper part of the Wymark and the lower part of the Seward Member, and Unit 4 correlates with the remainder of the Seward Member (see Fig. 65).

The Duperow Formation is a succession of sequential deposits separated from each other by sharp contacts. Each sequential deposit includes, in ascending order, several

7
Little Glen
12-12-10-14W2

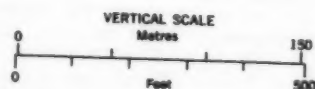
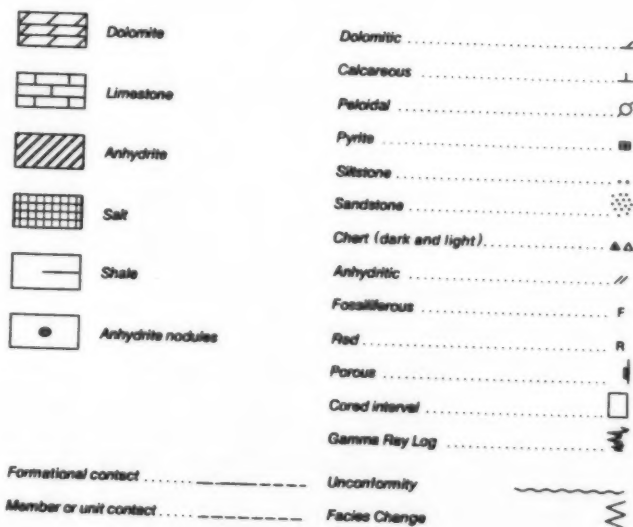
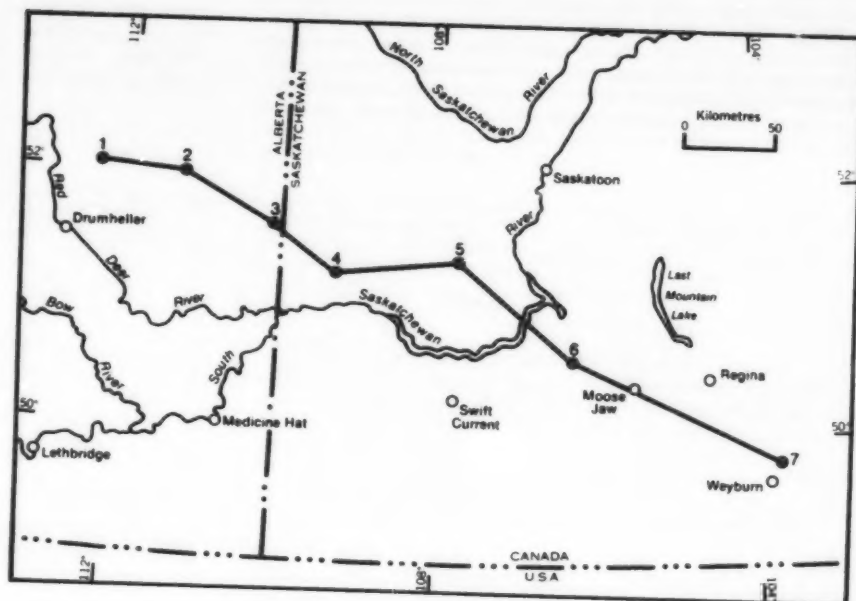
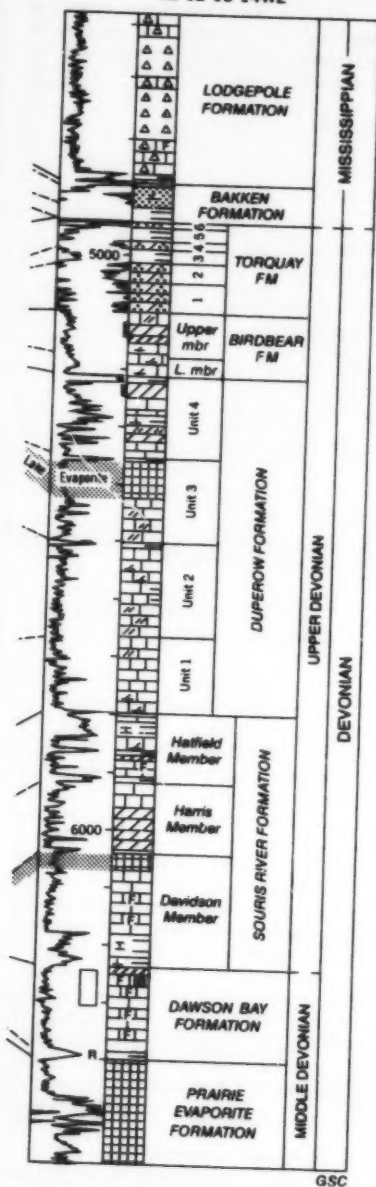


Figure 85. Stratigraphic cross-section, Upper Devonian strata, Alberta and Saskatchewan.

rock types which Wilson (1967) recognized: 1) a lower unit of fossiliferous limestone, either a stromatoporoidal limestone or a lime wackestone, with ostracodes, brachiopods and crinoids; 2) a middle unit consisting of three rock types with no preferred order (laminated, pelletal lime-mudstone; pelletal lime-grainstone; and fossiliferous lime-wackestone with remains of algae, gastropods, ostracodes, and calcispheres); 3) an upper unit of laminated lime-mudstone or greyish green, silty or sandy, laminated, microcrystalline dolostone. In complete

sequences, the greyish green, silty dolostone forms the top of the evaporitic cyclothem. The lithology and thickness of the evaporitic cyclothem vary from place to place within the Duperow Formation. Dunn (1975) recognized six lithologies in the complete cyclothem and described examples of several erosional features. He also discovered the presence of small erosional features in the evaporitic carbonates of the upper unit of the cyclothem, which he referred to as "firm grounds" and "hard grounds".

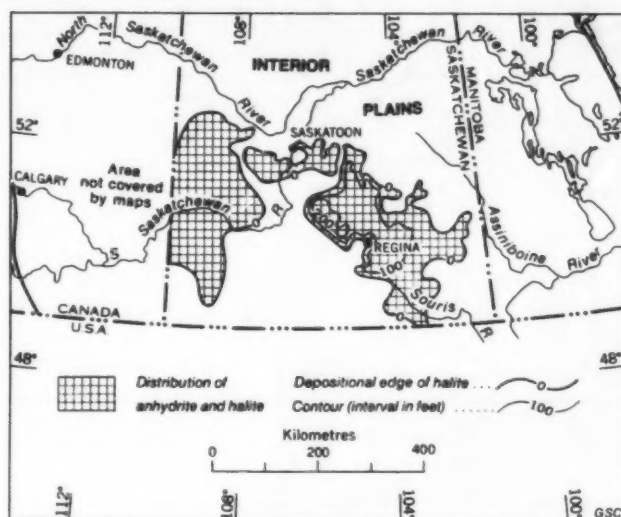


Figure 66. Isopach map, Davidson Evaporite, Saskatchewan.



Figure 67. Distribution of the "lower Harris halite", Souris River Formation, Saskatchewan.

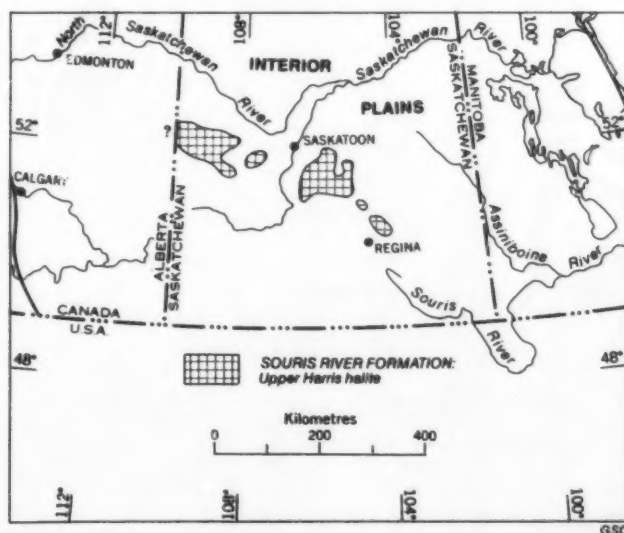


Figure 68. Distribution of the "upper Harris halite", Souris River Formation, Saskatchewan.

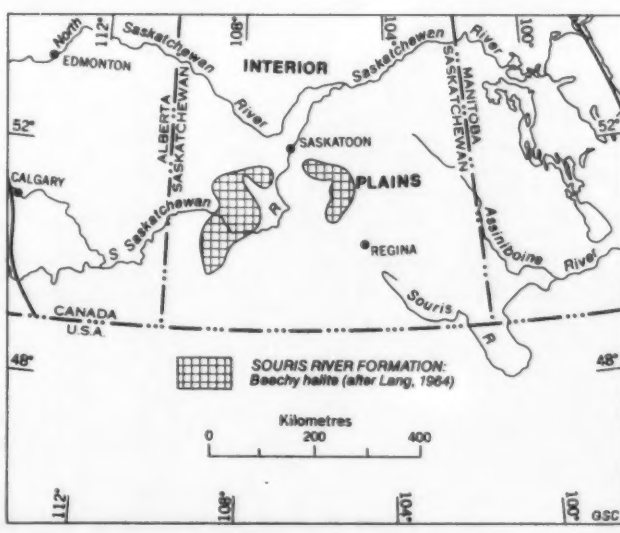


Figure 69. Distribution of Beechy halite, Souris River Formation, Saskatchewan.

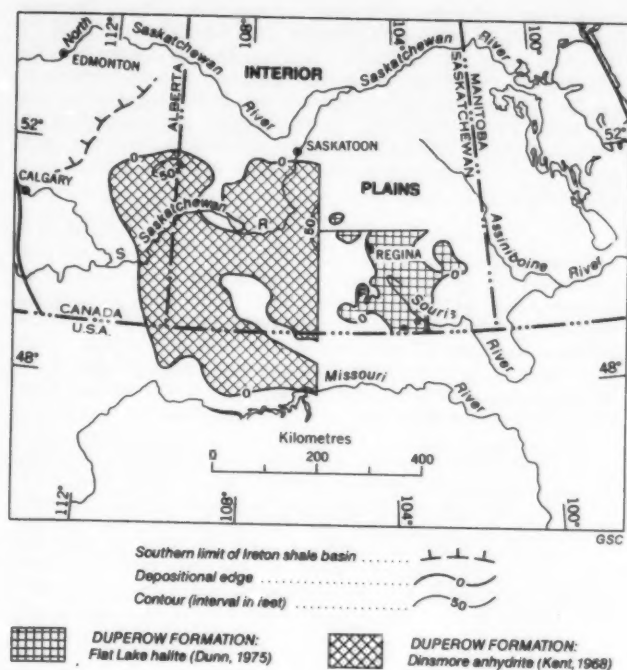


Figure 70. Isopach of Dinsmore Evaporite and distribution of Flat Lake Evaporite, Alberta.

The anhydrite deposits are relatively thin and widely distributed in southern Saskatchewan and southeastern Alberta. They were not mapped individually. In the Saskatoon Member, they are between 0.3 to 1.5 m (1-5 ft) thick. In the Wymark Member and its stratigraphic equivalents in southeastern Saskatchewan, the anhydritic beds are much thicker and are prominently present in the middle part of the member. They vary in thickness between 0.3 and 18.3 m (1 and 60 ft). In the Husky Phillips Etonia No. 1 well (located in Lsd. 1, Sec. 32, Tw. 26, Rge. 24, west of the 3rd meridian), the Wymark Member includes 15.2 m (50 ft) of halite in the middle part (see Fig. 65). Kent (1968) mapped the upper anhydrite unit in the Wymark Member under the name "Dinsmore Evaporite" (see Fig. 70). In southeastern Saskatchewan, Dunn (1975, Fig. 12) mapped a salt bed up to 21.9 m (72 ft) thick in the upper part of unit 3, which appears to be partly equivalent to the "Dinsmore Evaporite". He named this salt bed the "Flat Lake Evaporite" (see Fig. 65).

In the Seward Member and its equivalents, the anhydrite deposits vary in thickness between 0.3 and 3 m (1 to 10 ft), and they are scattered throughout the member. The Seward Member in Saskatchewan is more or less equivalent to the Peechee Member of the Southesk Formation of Belyea and McLaren (1957) in southeastern Alberta, which also contains interbeds of anhydrite, varying in thickness from 0.3 to 3 m (1 to 10 ft).

Evaporites of the Birdbear Formation. The Birdbear Formation (Sandberg and Hammond, 1958) was mapped in northern Montana, southeastern Alberta and southwestern Saskatchewan by Kent (1963, 1968). Kent (1968, figs. 3, 6) correlated the Lower member of the Birdbear Formation with

the Grotto Member of Belyea and McLaren (1957), and the uppermost anhydritic beds of the Upper member with the lower part of the Crowfoot Formation (see Fig. 65). The lower member of the formation consists of dolomitic siltstone, argillaceous limestone or dolostone and calcareous shale. In southwestern Saskatchewan, the Lower member locally includes anhydritic beds (Kent, 1963, figs. 3, 4). The Upper member includes non-argillaceous, in part fossiliferous, carbonates and interbeds of anhydrite. In southwestern Saskatchewan and southeastern Alberta, the anhydritic beds in the upper part of the Upper member are prominently developed.

The anhydritic beds of the Upper member in Saskatchewan are pale to dusky, yellowish brown, and crypto- to micro-crystalline (Kent, 1963, 1968). The equivalent anhydritic beds in the lower part of the Crowfoot Formation of southeastern Alberta are greyish brown and, in part, silty or sandy (Belyea and McLaren, 1957).

The Upper member of the Birdbear Formation was mapped by Kent (1968, Fig. 18) in southeastern Alberta and southwestern Saskatchewan and varies in thickness between 12.8 and 39 m (42 and 128 ft). The anhydritic beds were not mapped but were traced on several stratigraphic cross-sections in Saskatchewan and eastern Alberta. Their thickness varies between 1.5 and 25.4 m (5 and 80 ft).

Evaporites of the Torquay Formation. In order to avoid nomenclatural problems, Christopher (1961) proposed the name Torquay Formation for the strata previously mapped in the subsurface as the "Three Forks Formation" by Sandberg and Hammond (1958), the Stettler member of the Three Forks Formation of Kents (1959), and the "Potlatch Evaporite (restricted)" of Wilson (1955). The formation is equivalent to the upper part of the Crowfoot Formation of southern Alberta (Kents, 1959).

The Torquay Formation consists of light grey to reddish brown, micro- to finely-crystalline dolostone, in part silty and sandy, interbedded or nodular-interbedded with green, greenish grey, and dark reddish brown, dolomitic shale, and white to dark grey anhydrite. Christopher (1961) described the presence of sedimentary breccia beds, composed of subangular fragments and rounded, somewhat deformed, dolomitic mudstone pebbles in a dark brown mudstone matrix. The nodular-interbedding of light coloured dolomitic beds with dark brown and green argillaceous material produces a brecciated appearance. Erosional contacts are present between the argillaceous and dolomitic beds.

The Torquay Formation overlies the Birdbear Formation with a sharp contact. According to Kents (1959) and Christopher (1961) the contact is conformable but, according to Kent (1958), it represents a regional unconformity. Fuller (1956), Kents (1959), and Christopher (1961) subdivided the Torquay Formation into several units that can be recognized on electric logs (see Fig. 65). These electrolog units were traced without much change in thickness over a large area in Saskatchewan, notwithstanding the fact that contacts between the electrolog units are lithologically difficult to define in cores (Christopher, 1961). Kents (1959) noted that the formation becomes increasingly anhydritic in a northwest direction and that the reddish brown colours disappear in the same direction.

The isopach map of the Torquay Formation in Saskatchewan (Fig. 71) is redrawn from those of Kents (1959) and Christopher (1961). The formation was not mapped in Alberta, where a facies change to anhydritic and silty

dolostone occurs. The Torquay Formation is truncated in the subsurface by Mesozoic strata and does not extend north of the subcrop edge indicated in Figure 71. The thickness of the formation varies from 0 to 63.4 m (208 ft).

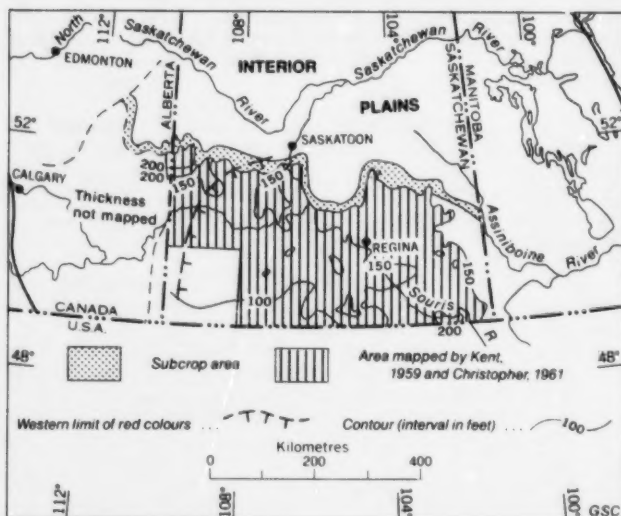


Figure 71. Isopach map, Torquay Formation.

Evaporites of the Crowfoot Formation. Belyea and McLaren (1957) proposed the name Crowfoot Formation for the evaporitic deposits situated between the Southesk and Stettler formations (see Fig. 64). They described the formation in the subsurface of southeastern Alberta from two sections that are far apart and different in thickness and lithology. In the Socony Craigmyle No. 4 well (located in Lsd. 17, Sec. 32, Tw. 32, Rge. 16, west of the 4th meridian), the section includes two units, a lower unit of light grey to grey anhydrite, and an upper unit of light coloured siltstone. The lower unit is equivalent to the Graminia and Calmar formations and to the lower part of the Stettler Formation, as defined by Wonfor and Andrichuck (1956). In the Royalite Crowfoot No. 2 well (located in Lsd. 4, Sec. 4, Tw. 21, Rge. 19, west of the 4th meridian), only the upper silty unit is present.

Regional correlations by Kent (1968) suggest that the lower anhydritic unit in the Craigmyle No. 1 well correlates with the upper part of the Birdbear Formation of southwestern Saskatchewan, and that the upper silty unit is equivalent to the Torquay Formation (see Fig. 65). Belyea (1964, figs. 6-17) correlated the Crowfoot Formation with the upper part of the Graminia Formation of central Alberta, which locally includes anhydrite (see Fig. 64).

The Crowfoot Formation is a poorly defined and inconsistently used map unit. There are no published isopach maps available. In the two wells from which the formation was originally described, the thicknesses are 3.9 and 38.1 m (13 and 125 ft).

Evaporites of the Stettler Formation. The Stettler Formation was defined by Wonfor and Andrichuck (1956) in the area east of Calgary, Alberta, as the succession of interbedded anhydrite, dolostone, and salt situated between the Calmar and Big Valley formations. In the same area, the Graminia Formation (see Fig. 64) cannot be mapped as a distinct unit and its equivalents are included in the lower part of the Stettler Formation (see Belyea and McLaren, 1957; Belyea, 1964).

The Stettler Formation consists of interbedded dolostone, anhydrite and salt (see Fig. 65). The lower part of the formation includes anhydrite, silty and sandy anhydrite, dolostone and argillaceous dolostone. This silty interval is overlain by a unit of anhydrite and dolomitic anhydrite, which includes interbeds of salt in the area east of Calgary. The upper part of the formation includes two thinly bedded, light brown to pink dolostone beds separated by a thin bed of dark grey limestone (Wonfor and Andrichuck, 1956).

An isopach map of the Stettler Formation in the area east of Calgary, prepared by Wonfor and Andrichuck (1956), indicates that its thickness in this region varies between about 122 and 213.4 m (400 and 700 ft). In the type section, the Canadian Gulf Jerard No. 1 well (located in Lsd. 16, Sec. 34, Tw. 37, Rge. 20, west of the 4th meridian), the formation includes two salt beds, 35 and 21.6 m (115 and 71 ft) thick (Wonfor and Andrichuck, 1956, p. 111). Salt beds are also present in several wells shown on the cross-sections published by Belyea (1955). The distribution of the Stettler Formation is shown in Figure 73.

Evaporites of the Hondo Formation. The interbedded anhydrite and dolostone succession in the subsurface east of Lesser Slave Lake, central Alberta, was first described by Belyea (1952) as the Hondo Member of the Woodbend Formation (Fig. 64). In the type section, the Barnsdall West Wabiskaw No. 1 well, located in Lsd. 11, Sec. 17, Tw. 78, Rge. 2, west of the 5th meridian, the Hondo Formation overlies finely to coarsely crystalline carbonates of the Grosmont Formation and is 96 m (315 ft) thick. In a later paper, Belyea (1956) considered the Hondo Formation as a facies equivalent of the Grosmont Formation, and she showed the transition between the Ireton, Grosmont, and Hondo formations as a facies change from shale to dolostone to interbedded dolostone and anhydrite. The cross-section on Figure 6-16 in Belyea (1964) suggests that the Hondo Formation includes only the evaporitic deposits within the Grosmont Formation.

The description of the Grosmont Formation by Cutler (1983) suggests that it would be more appropriate to regard the anhydritic deposits of the Hondo Formation as a member of the Grosmont Formation. According to that worker, the Grosmont Formation consists of four mappable units, each locally including anhydrite in the upper part. The anhydrite beds in the three lower units are only a few metres thick, but the anhydritic interval within the uppermost unit is up to 328 feet (100 m) thick and widely distributed. This anhydritic interval corresponds to the Hondo Formation and includes four lithofacies. These four lithofacies are: 1) intraclast breccia; 2) thinly interbedded dolostone and anhydrite; 3) interlaminated dolostone and anhydrite; and 4) *in situ* breccia. Only a relatively small amount of anhydrite is of a displacive or nodular form.

The distribution of the Hondo evaporites in central Alberta is sketchily shown in Belyea (1955, Fig. 1; 1964, Fig. 6-16) and Cutler (1983, Fig. 23). No isopach maps of the Hondo Formation have been published.

Evaporites of the Winterburn Group. The Graminia and Nisku formations of the Winterburn Group in central Alberta locally include minor amounts of anhydrite (Choquette, 1955; Exploration Staff Chevron Standard Ltd., 1979). In west-central Alberta, the upper part of the Winterburn Group includes massive interbeds of anhydrite and dolomitic anhydrite up to 70 feet (21 m) thick in the Simonette River area (Meijer Drees and Geldsetzer, 1984). The areal distribution of these evaporites and their relationship with the Crowfoot Formation is unknown.

Paleogeography

The depositional limits of the Upper Devonian succession are unknown because of pre-Cretaceous truncation. However, the original distribution of Upper Devonian rocks in the subsurface of Alberta and southern Saskatchewan is fairly complete and it is thus possible to reconstruct the local paleogeography. The successions in Manitoba and in the District of Mackenzie are incomplete at the top and interpretation of the paleogeographical situation in those regions cannot be made.

Two important paleogeographic features were present during the early Late Devonian, Frasnian Stage. The first one was the Peace River Arch, a paleotopographic feature situated in west-central Alberta, which was emergent in the area south of Fort St. John during the early part of the Frasnian Stage (see Bassett and Stout, 1967, Fig. 10). This high area is covered by a thin unit of carbonates of lagoonal character and surrounded by a reefal facies (see Fig. 72).

The second paleogeographic feature is a complex reefal barrier in southern Alberta, which restricted the flow of seawater in the area now occupied by North Dakota, Montana, Manitoba, southern Saskatchewan and southern Alberta. The barrier consists of stromatoporoid reefal mounds and coarse grained, biofragmental sediments. The shape and location of the barrier are variable and it is thus difficult to show, on one map, its distribution for the entire Late Devonian Period. Bassett and Stout (1967, Fig. 10) showed the barrier as a narrow, sinuous band, which includes the shelf margin reef complex, Big Valley-Stettler reef chain, the Bashaw reef complex, the Duhamel reef chain, and the Rimbey-Meadowbrook reef chain of the Leduc Formation, as mapped by Belyea (1955) and others in the subsurface of Alberta. They also include the Panther-Burnt Timber and Bourgeau-Hummingbird reef complexes of the Fairholme Group [as mapped by Dooze (1966, Fig. 51) and Belyea (1959, Fig. 1) from exposures in the Rocky Mountains of southern Alberta] in the reefal barrier (see Fig. 72).

Figure 72 also shows several other reefal mounds. The reefal mounds of the Swan Hills Formation in central Alberta are part of the Beaverhill Lake Group and are more or less equivalent to the lower part of the Souris River Formation. The Grosmont Reef complex in east-central Alberta is more or less equivalent to, but separate from, the Rimbey-Meadowbrook reef chain.

The paleogeography of the Late Devonian Period (the Famennian Stage) is distinct (see Fig. 73). The Peace River landmass had disappeared and there was no reefal barrier. Manitoba, Saskatchewan, and southeastern Alberta were part of a shallow embayment that gradually deepened

northwestward. Bassett and Stout (1967, Fig. 11) mapped six facies within the embayment, including normal marine, semi-restricted carbonates, restricted carbonates, and fine grained clastic sediments.

Environment of deposition

The evaporitic deposits of the Upper Devonian succession accumulated under a variety of sedimentary and diagenetic environments. The anhydrites, salt beds, and redbeds are similar to those described from the Middle Devonian Muskeg, Mirage Point, and Chinchaga formations.

The evaporitic deposits of the Slave Point, Souris River, Duperow, Birdbear, Stettler, and Hondo formations are interbedded with light coloured, microgranular, peloidal or fossiliferous carbonates, and greenish grey to reddish brown, argillaceous beds. Primary evaporitic deposits include clear and light grey halite, and light coloured, bedded, dolomitic anhydrite. Secondary evaporitic deposits are present as nodular anhydrite, replacement anhydrite, and halite-impregnated dolostone.

The presence of depositional sequences in the Souris River and Duperow formations (Lane, 1964; Wilson, 1967; Dent, 1968; Dunn, 1975), which include laminated, nodular, nodular-bedded or mosaic anhydrite in the upper part, suggests that the primary, laminated, dolomitic anhydrite accumulated as a result of increased salinity. At the end of each regressive cycle, the nearshore part of the embayment became very shallow and the inflow of seawater was restricted. The laminated anhydrite may represent a lagoonal, gypsiferous mud deposit. The secondary, nodular anhydrite was probably deposited in the shallow subsurface during periods of desiccation.

The salt beds are interbedded with anhydrite or greenish grey shale and locally contain chevron crystals. They are primary deposits. The distribution and the shape of the larger salt deposits suggest that they accumulated during regressive periods, in a lagoon or lake situated in the central part of the embayment. Other, less extensive, salt deposits may have accumulated in abandoned tidal channels.

The argillaceous deposits of the Torquay Formation in southern Saskatchewan are stained red by iron oxides. These red and pale green, dolomitic mudstones and breccia were described in detail by Christopher (1961). They resemble the anhydrite breccia in the upper part of the Muskeg Formation of central Alberta, and probably represent a nearshore lagoonal facies, which was altered during periods of exposure and weathering. The anhydrite and gypsum nodules are secondary deposits. The interbeds of anhydrite described by Christopher (1961) have nodular interbeds of shale and may be primary lagoonal deposits.

Structural geology

The evaporitic deposits of the Upper Devonian succession overlie the Middle Devonian beds and both have the same regional structural configuration. The beds form a homocline that dips toward the southwest at about 10 m/km (53 ft/mi) in southwestern Alberta, decreasing to between 4 and 6 m/km (23 and 32 ft/mi) in southeastern Alberta and southwestern Saskatchewan (Kent, 1968).

In Saskatchewan, the regional dip is greatly modified by the presence of local anomalies. Some of the anomalies were created by faults during the Laramide Orogeny, others are the result of collapse due to underground dissolution of Middle Devonian salt beds. These regional structural elements are indicated on the structural contour maps of the Lower member of the Birdbear Formation (Kent, 1968), the Torquay Formation (Christopher, 1961) and the Souris River Formation (Lane, 1964). They include the northwestern flank of Williston Basin, the Bow Island Arch, and the Alberta homocline (see Fig. 74). Local anomalies of tectonic origin are the Bowdoin Dome, the Cobourg Syncline, and the Kevin-Sunburst Dome. The unnamed anomalies are collapse structures associated with dissolution of salt. The large depression in the subsurface of Luck Lake, shown in Figure 34, is part of the "Rosetown Trough" of Kent (1968) or "Moose Jaw syncline" of Williams and Burk (1964, figs. 12-15). Some of the collapse structures were mapped in detail (see de Mille et al., 1964; Christiansen, 1967; Kent, 1968; Gorell and Alderman, 1968; Holter, 1969; and Meijer Drees, 1985).

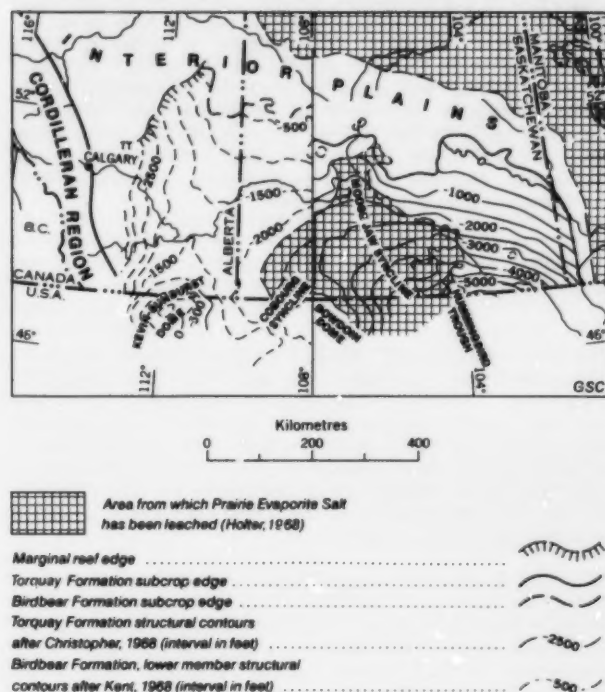


Figure 74. Composite structural contour map, Upper Devonian, Alberta and Saskatchewan.

CHAPTER V

HYDROLOGY

Introduction

Because the evaporitic deposits are soluble in water and there is abundant evidence in Western Canada that large parts of the evaporites were either altered or completely removed by the action of groundwater in the past, it was considered desirable to include in this report a chapter on hydrology. However, little is known about the flow of water in the deep subsurface and the process of salt dissolution. The following discussion is thus necessarily very general.

Surface water

Almost all surface water present in the Interior Plains of Western Canada has originated from precipitation and a large part of the water flows along the surface, or in the shallow subsurface, into the major river valleys that drain into Hudson Bay, the Gulf of Mexico, or the Pacific and Arctic oceans. Some water is kept at the surface in lakes, ice fields, and glaciers.

During the Pleistocene Period, a large part of the precipitation accumulated to form extensive ice fields and huge glaciers, which at times covered almost the entire region. At the end of the Pleistocene, the ice melted and a large amount of water was released to form lakes and rivers. The Pleistocene glacial deposits, the lake deposits, and the old river channels are still recognizable in the Interior Plains (see Prest, 1970).

Subsurface water

Four types of water occur in the subsurface of the Interior Plains: fresh water of meteoric origin; saline water buried along with the ancient sediments; mixtures of both; and brines derived from dissolution of halite.

The fresh water in the shallow subsurface is present in porous and permeable surficial glacial and fluvial deposits (Meyboom, 1967; and Brown, 1970). In places, it has entered porous beds of the underlying bedrock.

The saline water occurs mainly in the deep subsurface, where it is preserved within the porous rock formations. Because this formation water was buried along with the original sediments, and most of the bedrock in the Interior Plains and eastern Cordillera originated from marine deposits, it is not surprising to find that most aquifers are saline. The salinity of the formation water is variable.

In the areas of recharge, fresh water of meteoric origin has entered the subsurface aquifers and diluted the original salinity of the formation water. In the areas where salt is present in the subsurface, the deeper aquifers are highly saline (Hitchon, 1964).

Hitchon (1969a, b) has prepared hydraulic-head distribution maps for several groups of formations and for specific elevation intervals in the southern part of the Interior Plains, using data calculated from drillstem tests. These maps give a general picture of flow directions to be expected in the subsurface; however, they do not allow derivation of actual flow directions or rates, except where data are available on variations in permeability. The widespread, more or less continuous aquifers appear to control the overall northeastern flow pattern in the southern part of the western Interior Plains. The Foothills region of Alberta is the major recharge area for the Upper Paleozoic aquifers of Alberta and central Saskatchewan; the central Montana Uplift is the recharge area for meteoric waters flushing the Upper Paleozoic strata of southern Saskatchewan. The discharge area for the Paleozoic aquifers is located in the outcrop area along the southwestern margin of the Canadian Shield.

The Rocky Mountain Foothills and the Cypress Hills are important recharge areas for the Cretaceous aquifers of Saskatchewan. All the major river valleys in the Interior Plains act as areas of discharge (Hitchon, 1969a). The fluid flow in the Cretaceous aquifers is influenced by topography. Thus, drawdown associated with the major river valleys is important. The drawdown of the South Saskatchewan River is active at great depths, and Hitchon (1969a) considered this to have been an important factor in localizing the dissolution of Prairie Evaporite salt in the Elbow-Venn area south of Saskatoon. Downward moving recharge waters also have contributed to the dissolution of salt along the updip edge of the Devonian formations.

Hydraulic-head distribution maps are not available for the northern part of the Interior Plains of Western Canada, and the evaluation of the expected general flow of formation water in the subsurface is difficult to predict because of the presence of permafrost (see Owen, 1967).

Salt dissolution

Evidence for the influx of meteoric water and the redistribution of connate water in the Paleozoic strata of Saskatchewan is based on chemical research. The chloride content of several Paleozoic aquifers in Saskatchewan was mapped by Hitchon (1964), van Everdingen (1971), and Simpson and Dennison (1975). The variations in the chloride contents are related to the areal distribution of salt. Relatively low concentrations of chloride are found in the area southwest of the Paleozoic outcrop region and in those parts of southern Saskatchewan where salt is absent.

Recent work on the distribution of stable isotopes in the Paleozoic aquifers of Saskatchewan suggests that the halo of highly saline formation water, which surrounds the Devonian salt beds in the subsurface of southern Saskatchewan, is partly of marine origin and partly of meteoric origin (Hitchon and Friedman, 1969; Hitchon et al., 1971). The explanation offered by Hitchon is that, during the several periods of uplift and erosion that occurred in Late Paleozoic, Early Mesozoic and Cenozoic time, fresh water entered the Paleozoic aquifers and partly replaced the original connate salt water. During these periods, the upper

part of the Paleozoic succession was exposed at the surface, and the salt beds were locally dissolved by circulating groundwater. During Late Mesozoic time, the Paleozoic succession was flooded by the sea and buried under marine deposits of Cretaceous age. At this stage, the influx of meteoric water must have halted. We can conclude that a period followed in which the salt was dissolved by diffusion, because the meteoric water that entered the Paleozoic succession during the preceding period was highly saline, and in chemical equilibrium with the connate water of the impermeable rocks, which are in direct contact with the Devonian salt beds. During the Cenozoic Period, the Paleozoic and Mesozoic rock succession was uplifted again and there is evidence that, at present, salt is being removed for the second time by the action of circulating groundwater.

Where Paleozoic rocks are exposed in northern Alberta, central Saskatchewan, and southwestern Manitoba, saline water is being discharged in the form of saline springs (see Meyboom, 1967). The chemistry of the saline spring water indicates that it has a meteoric origin, and the conclusion is that the salts are derived from the halite and gypsum beds present in the subsurface farther south (Hitchon et al., 1971).

Reports by van Everdingen (1971) on the saline springs in Manitoba, by Baar (1972) on observations in potash mines, and by Christiansen (1967, 1971) and Gendzwill and Hajnal (1971) on Recent collapse structures at the surface, indicate that salt is being dissolved as far south as the present-day salt edge indicated in Figure 51.

CHAPTER VI

ECONOMIC GEOLOGY

Introduction

The evaporitic deposits of Western Canada, which include gypsum, salt, and potash, are used as a source for raw materials. Salt beds are also useful host rocks for man-made, underground caverns in which natural gas can be stored. If it were not for the presence of impermeable anhydritic cap rocks, several oil and gas fields in Alberta, Saskatchewan and Manitoba would not exist. Some oil and gas accumulations also occur in structural traps which resulted from collapse due to dissolution of salt in the underlying strata (see Smith and Pullen, 1967).

Some geologists believe that the process by which the evaporites accumulated may have played a role in the accumulation of certain types of lead and zinc ore deposits (see Jackson and Beales, 1967). The fact is that galena, sphalerite, and barite are commonly found in the Great Slave and Cordilleran regions in a white, very coarsely crystalline dolostone facies, which is similar to the brecciated dolostone in surface exposures of units known to include evaporitic deposits in the subsurface.

Sodium chloride

Sodium chloride or "kitchen" salt is produced for industrial and domestic use in Manitoba, Saskatchewan, and Alberta. In 1974, the three provinces produced 680,000 tons of salt valued at 9.3 million dollars. In Saskatchewan, the salt is produced by dissolution *in situ* ("brining") or by conventional mining, along with potash. Northern Industrial Chemicals of Saskatoon extracts salt by dissolution *in situ* from the Leofnard Salt of the Prairie Evaporite Formation for the production of caustic soda and chlorine. Domtar Chemicals uses the same method to obtain salt from the Leofnard Member for evaporation and fusion. The Canadian Salt Company produces sodium chloride from the Leofnard Member at Belle Plaine as a byproduct from the extraction of potash salt by dissolution *in situ*.

The Alberta Dow Chemical Company of Canada extracts salt from the Upper Lotsberg and Leofnard Salt beds at Fort Saskatchewan by dissolution *in situ* to manufacture caustic soda and chlorine. The Canadian Salt Company uses the brine from the Leofnard Salt near Lindberg for evaporation and fusion, and Dow Chemical Ltd. obtains salt from the upper Lotsberg Salt at Duvernay. In Manitoba, a small amount of salt is produced from natural brines in the subsurface near Brandon and is used to make caustic soda and chlorine. The natural brines are probably in contact with the Leofnard Salt of the Prairie Evaporite Formation.

Potassium chloride

The saline springs in the Devonian outcrop area west of Lake Winnipegosis and Lake Manitoba contain potassium

chloride (Tyrrell, 1892). Kindle (1914) suggested that possible potash deposits could occur in the Devonian beds or in the Jurassic (Amaranth Formation) gypsum and anhydrite beds near Gypsumville, Manitoba. However, it was not until much later that potash was actually found in the subsurface.

A well drilled in 1943 by Imperial Oil Ltd. near Radville, in southern Saskatchewan, encountered salt containing potash beds at a depth greater than 2317 m (7600 ft) (Cheesman, 1958). The first significant potash ore deposit was discovered in 1946 in the Verbata No. 2 well, drilled near Unity, southwestern Saskatchewan, and, in 1958, the Potash Company of America produced potash salt from a mine shaft started in 1956.

Presently, potash is being produced in nine mines, all located in Saskatchewan, and the production between the years 1973 and 1975 amounted to 24 per cent of total world production. Potash salt is being extracted by underground dissolution at a depth of more than 152.4 m (500 ft) in one mine near Belle Plaine, west of Regina. Eight conventional mines, in which the room-and-pillar method of excavation is employed, are located east and west of Saskatoon and near Esterhazy, southeast of Yorkton (see Fig. 75).

The potash beds in southern Saskatchewan occur in three zones. They were mapped by Holter (1969, 1972) and named in ascending order the Esterhazy, Belle Plaine, and Patience Lake beds.

Calcium sulphate

Gypsum and anhydrite deposits are presently mined only in British Columbia and in Manitoba (see Fig. 75). In British Columbia, Western Gypsum Mines extract gypsum from the Burnais Formation near Windermere. The production in 1974 was a little over 440,000 tons. All of it was used in the manufacture of plaster and cement. Gypsum is also mined near Kamloops by Falkland Gypsum from lenses that occur closely associated with faults in the Permian Cache Creek Group. These deposits have been regarded as hydrothermal; however, Baird (1964) has suggested that the gypsum may be of sedimentary origin.

In Manitoba, Domtar Construction quarries the gypsum deposits of the Amaranth Formation near Gypsumville, and Westroc Industries operate a shallow mine near Silver Plains. The combined production in 1974 was about 207,000 tons and most of it was used in the manufacture of plaster and cement. Large quantities of gypsum and anhydrite are present near the surface in Alberta and the District of Mackenzie, Northwest Territories, but at present the demand for gypsum is rather limited.

Storage caverns

In Alberta and Saskatchewan, natural gas and liquid gas products are stored in underground caverns formed by dissolution of salt (see Fig. 75). The caverns in the Leofnard Salt of the Prairie Evaporite Formation near Hardisty and Hughenden, Alberta, and the storage caverns in the upper

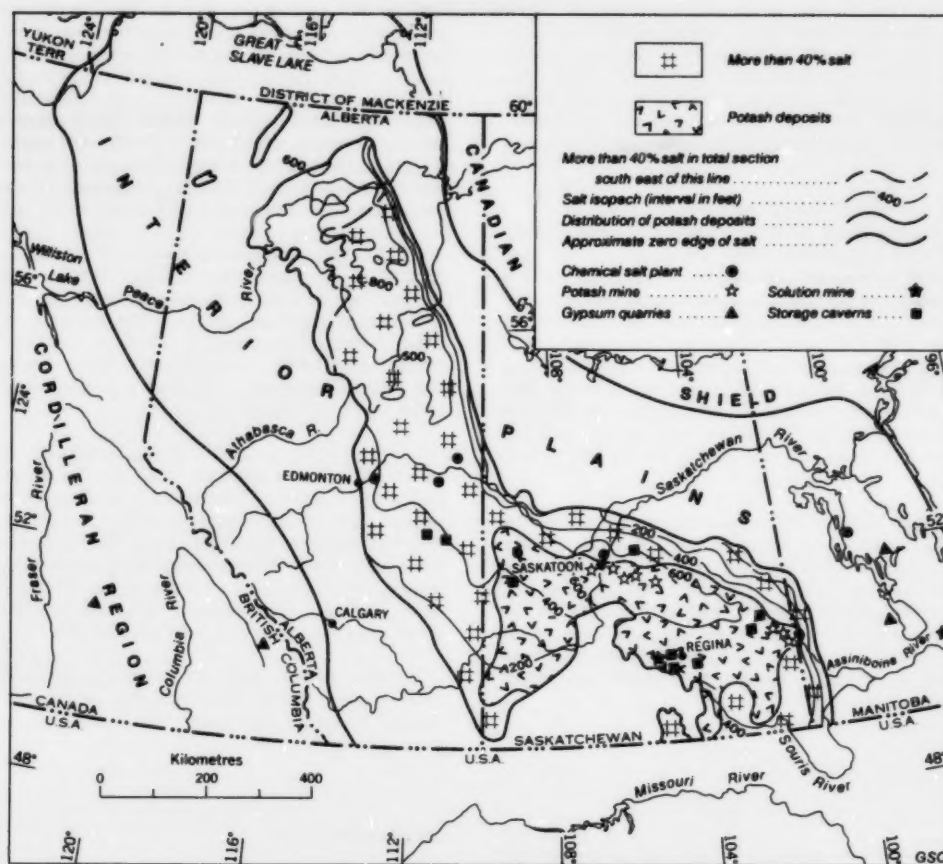


Figure 75. Location of potash and salt mines, storage caverns and gypsum quarries, Western Canada.

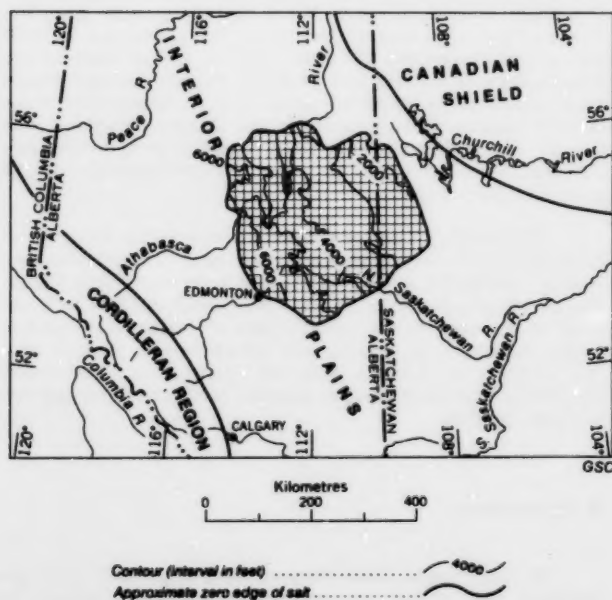


Figure 76. Depth to Upper Lotsberg Salt, Alberta and Saskatchewan.

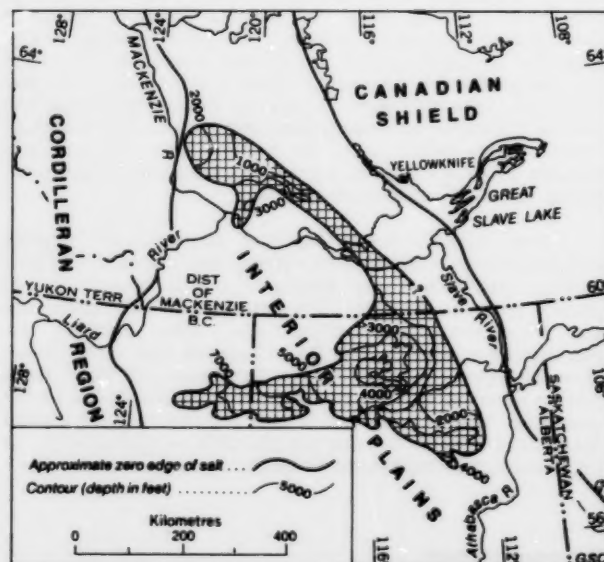


Figure 77. Depth to Cold Lake Salt, northern Alberta and District of Mackenzie.

Waste disposal

In the future, subsurface salt beds of Alberta and Saskatchewan may be used for the disposal or storage of toxic chemicals and radioactive material. In order to evaluate storage potential, some knowledge is required of the distribution, thickness, depth, purity and stability of the salt beds and the overlying rocks. The isopach maps of the different salt beds and the depth-to-salt maps, which accompany this report, should be helpful in this regard. Nevertheless, many other considerations need to be investigated before a decision can be reached concerning the possible use of a specific salt bed as a host rock for storage of waste. The reader is referred to the reports of Simpson and Dennison (1975) and Meijer Drees (1985) for more information.

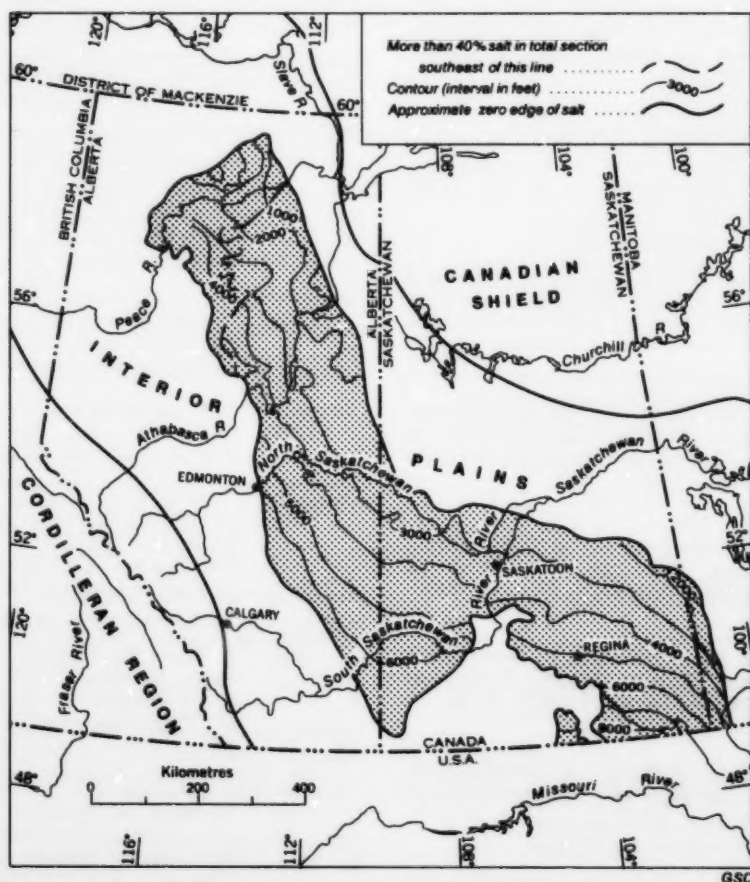


Figure 78. Depth to Prairie Evaporite salt, Alberta and Saskatchewan.

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MAPS NOT

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